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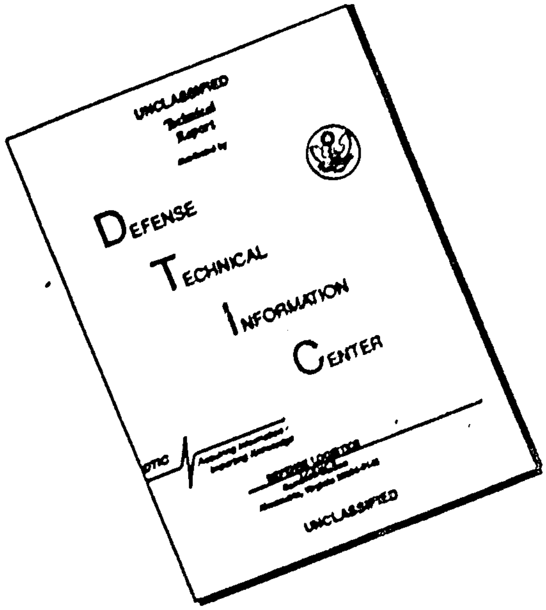

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THE JOINING OF DISSIMILAR METALS

by

H. E. Pattee, R. M. Evans, and R. E. Monroe

to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus, Ohio 43201

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by

H. E. Pattee, R. M. Evans, and R. E. Monroe*

SUMMARY

The joining of dissimilar metals has progressed significantly during the past two decades because of the increasing use of dissimilar-metal combinations in the aerospace, nuclear, chemical, and electronics industries. The selection and application of dissimilar metals in structural applications are dictated by the service requirements of the structure, as well as the economics of material cost and the ease of fabrication. Requirements of a structure for high-temperature strength, lightness, oxidation resistance, corrosion resistance, or other desirable properties may lead to the use of dissimilar-metal combinations in its design, with an attendant need for a method of joining the dissimilar metals.

Dissimilar-metal-joining procedures can be applied in two ways. The dissimilar-metal joint can be an integral part of a structure; in such cases, the effects of joining on the properties of the joint members must be carefully considered. In other instances, the dissimilar-metal joint is incorporated in a relatively short transition section that is inserted between various structural members and welded or brazed in place; joining occurs between similar or identical metals when a transition section is used, and few problems are encountered with a well-designed section of this nature. The dissimilar-metal joint in the transition section can often be made with processes that would be impractical for joining structural parts themselves, e.g., friction welding, explosive welding, etc.

In this report, the dissimilar-metal joining between the following metals and alloys is emphasized: (1) aluminum, titanium, and beryllium, and their alloys, (2) refractory metals and alloys, and (3) high-strength steels and other high-strength, heat-resistant alloys. Dissimilar-metal joints in structures having aerospace applications are emphasized. Joining technology is discussed in the following major sections:

(1) Joining dissimilar ferrous metals
(2) Joining nonferrous to ferrous metals
(3) Joining dissimilar nonferrous metals.

*Senior Electrical Engineer, Associate Chief and Division Chief, respectively, Materials Joining Division, Battelle-Columbus Laboratories.

INTRODUCTION

The joining of dissimilar metals has become increasingly important during the past two decades because of the service requirements for structures used in missiles and rockets, supersonic aircraft, and nuclear equipment. While certain dissimilar metals have been routinely joined for many years, the advent of the space and nuclear ages has produced a need for sophisticated methods to join the new structural alloys that have been developed for these demanding applications. These alloys possess exceptional mechanical properties and resistance to corrosive media under extreme operating conditions. However, such alloys are frequently used only for sections of a structure where their specific properties are required; conventional alloys are used for the remainder of the structure for reasons of economy, weight, ease of fabrication, etc. Thus, there is a need for procedures to produce reliable joints between dissimilar metals. The ability to design and fabricate such joints is essential to many segments of our industrial economy, particularly those associated with the production of aerospace hardware, chemical equipment, nuclear apparatus, and electronic devices.

The selection and use of dissimilar metals in structural applications is governed by the service requirements for the structure and the economics of material cost and fabrication. For example, a relatively inexpensive grade of steel may be used in fabricating the shell of a vessel for the chemical industry for reasons of economy, while the corrosion requirements are satisfied by lining the vessel with thin-gage stainless steel or titanium. Because of their low density, aluminum alloys are used extensively for tankage in liquid-fueled rockets; however, the plumbing to distribute and control the flow of the fuel and oxidizer to the engines is fabricated from stainless steel. Other applications requiring the joining of dissimilar metals are discussed briefly below:

(1) The lunar module contains 26 pressure vessels in its descent and ascent stages.[(1)*] Depending on their function, these vessels are fabricated from titanium-, nickel-, aluminum-, or iron-base alloys. Coextruded titanium-stainless steel transition joints are used to connect the titanium pressure vessels to the stainless steel feed system. Metallurgically bonded transition joints are also used to join aluminum to stainless steel components.

(2) Joints between beryllium and such metals as aluminum, stainless steel, and titanium are encountered in space-vehicle design where beryllium is an attractive structural metal because of its low density, its stiffness under load, and its resistance to damage by impact with meteors.

(3) Procedures are required to join dissimilar metals in nuclear-reactor construction. These applications range from the cladding of fuel elements with aluminum, stainless steel, or zirconium alloys to the fabrication of dissimilar-metal piping joints.

(4) Dissimilar-metal joints are encountered in aircraft hydraulic and ducting systems, as well as in engine and airframe construction. While significant quantities of titanium alloys will be used in the supersonic transport, there will be occasion to join titanium to other structural alloys to meet specific design requirements.

(5) Dissimilar-metal joining is used extensively in the electronic industry. Typical applications include the attachment of lead wires and connectors to semiconductor devices, the fabrication of vacuum-tube components, and the construction of special-purpose tubes for high-frequency operation.

In general, dissimilar metals are used in a structure to provide high-temperature or low-temperature strength; resistance to oxidation, corrosion, or wear; resistance to radiation damage; or other required properties. Also, the use of dissimilar metals is often attractive from the cost standpoint.

An up-to-date review of developments in the technology of joining dissimilar metals is presented in this report, with emphasis on the methods used to join specific metal combinations. From the material aspect, the metals of interest to the Defense Metals Information Center (DMIC) are emphasized. Included in this classification are (1) aluminum, titanium, and beryllium, and their alloys, (2) refractory metals and their alloys, and (3) high-strength steels and other high-strength, heat-resistant alloys. For reporting purposes, dissimilar metals are defined as metals that differ substantially in composition and properties. For example, the joining of stainless steel to titanium and its alloys is discussed in this report, but the joining of various stainless steels or titanium alloys to each other is not included. Although both fusion and nonfusion methods to join dissimilar metals are covered, the nonfusion processes are emphasized, since they are more useful in joining metals with widely differing compositions and properties.

The sources of information for this publication include the reports of Government and industry

*References are given on page 40.

that are filed by DMIC, the technical literature on joining dissimilar metals, the libraries of the Columbus Laboratories of Battelle Memorial Institute, various engineering indexes, and personal files. References to both domestic and foreign developments in this field are included. The literature reflects the pace of developments in this area of technology, since most publications are dated in the past 10 years.

In the case of Government-sponsored research, the results often appear in a technical paper or article, as well as in a report to the sponsoring agency. While the formal report is cited as the primary information source, the papers and articles are referenced also for those who do not have ready access to Government reports.

A number of general survey articles on the joining of specific dissimilar-metal combinations have been published in recent years. While such articles become rapidly dated by current developments, their value should not be discounted, because they indicate the dissimilar metals that have been joined. For example, in 1962 Peckner prepared a list of 170 dissimilar metals that had been joined for Materials in Design Engineering.(1) This list is reproduced as Table 1, and includes the joining method, the filler metal, the relative difficulty of making the joint, and comments regarding the joint properties; the source of the data is indicated as well. An article of a similar nature in which advanced joining procedures are reviewed has been prepared more recently by Irving.(2) General articles summarizing the progress made in joining dissimilar metals by diffusion welding, brazing, and explosive welding have been prepared also.(3-6)

BACKGROUND

Joining Considerations

The joining of dissimilar metals is inherently more difficult than the joining of similar or identical metals because of the differences in the physical, mechanical, and metallurgical properties of the metals being joined. Difficulties associated with joining metals whose physical properties (melting temperature, coefficient of linear expansion, thermal conductivity, and specific heat) differ markedly can often be anticipated and minimized by proper selection of the joining process or by modification of the joining technique. For example, when metals with substantially different coefficients of expansion are fusion welded, they expand and contract at different rates to produce stresses that can cause cracking or fissuring of the weld metal; this problem can be minimized by proper joint design and the use of a ductile filler metal. If metals with widely differing melting temperatures are welded, one metal will be molten long before the other metal has reached the welding temperature; a welding technique in which the arc is concentrated on the metal having the higher melting temperature has been used to produce acceptable joints. However, such metals can often be brazed or diffusion welded without difficulty.

The problems associated with the metallurgical compatibility dissimilar metals are more serious and more subtle than those discussed above, and a thorough understanding of the phenomena that occur during joining is essential for their solution. Such difficulties can be overcome sometimes by proper selection of the filler metal; in other instances a special joining technique is required. The examples discussed below indicate the magnitude of the problems encountered.

(1) Nickel and copper can be readily fusion welded because these metals are metallurgically compatible; regardless of composition these metals form a series of solid solutions. Thus, Monel, a nickel-copper alloy, can be welded to pure nickel without difficulty. However, when a stainless steel filler wire is used to weld Monel to an austenitic stainless steel, the weld will be hot short and crack sensitive if there is any appreciable copper pickup from the Monel. These metals can be successfully welded with a special Inconel filler metal and a technique that minimizes weld-metal dilution.

(2) The joining of aluminum to ferrous metals is much more difficult than the rather simple example cited above, because the physical properties of these metals differ widely and they are metallurgically incompatible as well. Aluminum melts at 1220 F while iron melts at 2797 F; the coefficients of linear expansion for aluminum and iron are 13.6×10^{-6} and 6.5×10^{-6} in./in./F, respectively. Also, the thermal conductivities and specific heats of these metals differ considerably. The iron-aluminum phase diagram indicates that these metals form solid solutions, intermetallic compounds, and a eutectic. Several complex intermetallic compounds, such as $FeAl_3$, Fe_2Al_7, Fe_2Al_5, $FeAl_2$, and FeAl, form when the iron content of an aluminum-iron alloy exceeds 40 percent; alloys of iron and aluminum have little or no ductility when the iron content exceeds 12 percent. When aluminum and steel are fusion welded, the molten metals react to form a hard, brittle layer consisting mainly of $FeAl_3$. However, procedures to minimize the formation of such compounds during fusion welding have been developed. In brief,

TABLE I. GUIDE FOR JOINING DISSIMILAR METALS (I)

Combination		Joining Method	Rel. Diff.	Filler	Other Comments	Source
ALUMINUM AND ALUMINUM-BASE ALLOYS						
Aluminum	Austenitic Stainless	Friction weld	Easy	—	Poor joint ductility	Amer. Mach. & Fdy. (AMF)
	Brass	Friction weld	Easy	—	Poor joint ductility	
	Copper-Base Alloys	Flash weld	Easy	—	Fair joint ductility	Alcoa
		Alcoa R-260	Easy	—	Poor joint ductility	Republic Aviation
		Braze	Mod. difficult	Al-base	Poor joint ductility	Alcoa
		Electron beam	Easy	—	Brittle, vacuum tight joint	Hamilton-Standard
		Friction weld	Easy	—	Poor joint ductility. Use at 400 F max	AMF
		Hard solder	Easy	Zn-base	Fair joint ductility	Alcoa
		Soft solder	Easy	Sn-base	Good joint ductility. Use zincate coating and copper plate aluminum	Bell Labs
		Diffusion bond	Easy	—	Poor joint ductility	Alcoa
		Pressure weld	Easy	—	Poor to good joint ductility	
	Ferrous-Base Alloys	Torch weld	Mod. difficult	Al-base	Brittle joint. Use joint up to 800 F	
		Arc weld	Easy-	Al-base	Joint ductility fair. Use joint up to 800 F	
		Resistance weld	Mod. difficult	—	Joint ductility fair. Use joint up to 800 F	
		Hard solder	Easy	Zn-base	Joint ductility good. Use joint up to 500 F	
		Soft solder	Easy	Sn-base	Joint ductility good. Use joint up to 250 F	
		Diffusion bond	Easy	Ag electroplate	Joint ductility good. Use joint up to 600 F	
		Pressure weld	Easy	—	Joint ductility good. Use joint up to 800 F	
		Braze	Easy	Al-base	Joint ductility fair. Use joint up to 800 F	
	Lead-Base Alloys	Soft solder	Easy	Sn-base	Good joint ductility	
		Pressure weld	Easy	—	Good joint ductility	
	Magnesium	Forge weld	Easy	—	Somewhat brittle joint	Dow
		Flux dip braze	Easy	Powdered Al	Brittle joint	
		Ultrasonic weld	Mod. difficult	—	Brittle joint	
		Soldering	Mod. difficult	70Sn-30Zn	Brittle joint	
	Nickel-Base Alloys	Same as Aluminum-Ferrous alloys				
	Precious Metals	Soft solder	Easy	Sn-base	Good joint ductility	Alcoa
		Diffusion bond	Easy	—	Good joint ductility	
		Pressure weld	Easy	—	Good joint ductility	
	Silver-Base Alloys	Hard solder	Easy	Zn-base	Fair to good joint ductility	
		Soft solder	Easy	Sn-base	Fair to good joint ductility	
		Diffusion bond	Easy	—	Fair to good joint ductility	
		Pressure weld	Easy	—	Fair to good joint ductility	
	Steel	Al-Fin or Bi-Braze	Mod. difficult	Pure [illegible]	Poor joint ductility, poor fatigue characteristics. Bonds high heat conductor to low heat conductor	Republic Aviation
		Shielded metal arc	Mod. difficult	25M bronze rod, Ag brazing alloy, 1100 Al	Use oxyacetylene, tin edge of steel with bronze; heliarc weld Ag strip to tinned edge; heliarc weld Al to Ag strip	Union Carbide Nuclear
	Tin-Base Alloys	Soft solder	Easy	Sn-base	Good joint ductility	Alcoa
		Pressure weld	Easy	—	Good joint ductility	
	Titanium-Base Alloys	Braze	Easy	Al-base	Fair to good joint ductility	
		Hard solder	Mod. difficult	Zn-base	Fair to good joint ductility	
		Soft solder	Easy	Sn-base	Fair to good joint ductility	
		Resistance weld	Mod. difficult	—	Forms weak braze type joint	Titanium Metals
	Tungsten	Arc weld	Mod. difficult	Al-base	Good joint ductility	Alcoa
	Uranium	Braze	Easy	Al-base	Fair joint ductility	
	Zinc-Base Alloys	Hard solder	Easy	Zn-base	Good joint ductility	
		Soft solder	Easy	Sn-base	Good joint ductility	
		Pressure weld	Easy	—	Good joint ductility	
1100	Beryllium	Ultrasonic weld	Easy	—	—	Sonobond
	Beryllium + Al layer	Ultrasonic weld	Easy	—	—	
	Copper	Ultrasonic weld	Easy	—	—	
	Iron	Ultrasonic weld	Easy	—	—	
	302 Stainless Steel	Ultrasonic weld	Easy	—	—	

Combination		Joining Method	Rel. Diff.	Filler	Other Comments	Source
ALUMINUM AND ALUMINUM-BASE ALLOYS (continued)						
2014	Chromel Wire	Ultrasonic weld	Easy	—	—	Sonobond
	Constantan Wire	Ultrasonic weld	Easy	—	—	
	Copper	Ultrasonic weld	Easy	—	—	
	301 Stainless Steel	Ultrasonic weld	Easy	—	—	
	321 Stainless Steel	Ultrasonic weld	Easy	—	—	
2024	Beryllium	Ultrasonic weld	Easy	—	—	
	Iron	Ultrasonic weld	Easy	—	—	
	AISI 1010	Ultrasonic weld	Easy	—	—	
3003	Copper	Ultrasonic weld	Easy	—	—	
M252	Mo-0.5Ti	Braze	Easy	Sterling silver	Use inert gas brazing	Boeing
BERYLLIUM						
Beryllium	Austenitic Stainless	Induction braze	Mod. difficult	60Pd-40Ni	Recommended for joining small sections. Used in high temp valve components	UCC Nuclear
	Beryllium copper	Electron beam	Easy	—	Joint ductility equal to beryllium	Hamilton-Standard
COPPER AND COPPER-BASE ALLOYS						
Aluminum Bronze	Steel	Shielded metal arc	Easy	Ambraloy 928	Long arc (½ in.) to reduce iron pickup	UCC Nuclear
Beryllium Copper	Mild Steel	Thermatool Electron beam	Easy Easy	— —	Joint brittle, must be tempered Joint ductility equals beryllium copper	AMF Hamilton-Standard
	Tungsten	Electron beam	Easy	—	Joint ductility equivalent to tungsten	
Brass	Austenitic Stainless	Friction weld	Easy	—	Fair to poor joint ductility	AMF
	Dumet	Percussion weld	Easy	—	Good joint ductility	General Electric
	Palladium	Projection weld	Easy	—	—	Fansteel Met.
	Platinum	Projection weld	Easy	—	—	
	Silver	Projection weld	Mod. difficult	—	—	
	Steel	Projection weld	Easy	—	—	
Bronze	Silver	Projection weld	Easy	—	—	
	Steel	Projection weld	Easy	—	—	
Copper	Austenitic Stainless	Solder Braze	Easy Easy Mod. difficult	Sn-Pb alloys Silver braze alloys Electroless Ni	Good joint ductility. Use corrosive flux or solderable plating on stainless Good joint ductility. Use low carbon or stabilized stainless Special service over 1500 F	Bell Labs UCC Nuclear
	Brass	Friction weld Solder Braze	Easy Easy Easy	— Sn-Pb alloys Silver braze alloys	Excellent joint ductility Good joint ductility Good joint ductility. Avoid leaded brass	AMF Bell Labs
	Dumet	Percussion weld	Easy	—	Excellent joint ductility	General Electric
	Galvanized Steel	Solder	Easy	Zn-Al alloy	Flux not required. Rubbing action needed for solder	Bell Labs
	Kovar	Percussion weld	Easy	—	Excellent joint ductility	General Electric
	Magnesium	[illegible] weld Flash weld	Mod. difficult Easy	— —	Probably brittle joint. Good only for electrical connections Joint probably brittle. Joint strength up to 25-28,000 psi	Dow
	Nickel	Solder Braze Electron beam	Easy Easy Easy	Sn-Pb alloys Silver braze alloys —	Good joint ductility Good joint ductility Good joint ductility	Bell Labs Hamilton-Standard
	Stainless Steel	Friction weld Tungsten arc	Easy Mod. difficult	— —	Poor joint ductility Slight intergranular penetration of Cu into stainless	AMF UCC Nuclear
	Steel	Solder Braze Thermatool Manual arc	Easy Easy Difficult Mod. difficult	Sn-Pb alloys Ag braze alloys Al alloy — Bronze Arc D	Good joint ductility Good joint ductility Aluminum cladding needed on steel Good joint ductility Butter steel with Inco 141 electrode	Bell Labs AMF U. S. Steel

Combination		Joining Method	Rel. Diff.	Filler	Other Comments	Source
COPPER AND COPPER-BASE ALLOYS (continued)						
Nickel Silver	Brass	Projection weld	Easy	—	Joint ductile	Fansteel Met.
OF Copper	AISI 4130	Electron beam	Easy	—	Joint ductility equiv to least ductile part	Hamilton-Standard
Oxidized Copper	Steel	Shielded metal arc	Easy	Anaconda 372	Preheat to 400 F	UCC Nuclear
IRON AND IRON-BASE ALLOYS						
A286	Inco 100	Electron beam	Easy	—	Joint ductility equivalent to least ductile part	Hamilton-Standard
	Inco 713	Electron beam	Easy	—	Joint ductility equiv to least ductile part	↓
	Ud[illegible]	Electron beam	Easy	—	Joint ductility equiv to least ductile part	↓
Cast Iron	Stainless Steel	Tungsten arc	Easy Easy	Ni and stainless Everdur	Deposit Ni bead on edge of cast iron; weld bead to stainless with stainless rod Direct arc on stainless, not cast iron	UCC Nuclear ↓
Dumet	Austenitic Stainless	Percussion weld	Easy	—	Excellent joint ductility	General Electric
	Kovar	Percussion weld	Easy	—	Excellent joint ductility	↓
	Nickel	Percussion weld	Easy	—	Excellent joint ductility	↓
	Molybdenum	Percussion weld	Easy	—	Excellent joint ductility	↓
	Tungsten	Percussion weld	Easy	—	Excellent joint ductility	↓
Iron-Base	Nickel	Arc weld Braze	Mod. difficult Mod. difficult	High Ni wire Ag or Cu	Poor joint ductility Poor joint ductility	Republic Aviation ↓
Kovar	Austenitic Stainless	TIG weld Braze	Mod. difficult	— Cu or 82Au-18Ni	Joint ductile. Large diff in coef of exp Good joint ductility. Use reducing atm. Use joint up to ~ 750 F	Westinghouse
	Ferritic Stainless	Braze TIG weld Resistance weld	Mod. difficult Easy Easy	72Ag-28Cu —	Good ductility. Use reducing furnace atm Good ductility. Use reducing furnace atm Good ductility. Use reducing furnace atm	↓
	Nickel	Electron beam Percussion weld Resistance weld Braze TIG weld	Easy Easy Easy Mod. difficult Easy Easy	— — — Al 72Ag-28Cu —	Excellent joint ductility Excellent joint ductility Brittle joint. Max use temp ~ 500 F Brittle joint. Max use temp ~ 500 F No P-bearing brazing alloys. Anneal Kovar Good joint ductility	Hamilton-Standard General Electric Westinghouse
	Titanium	Resistance weld Braze	Easy Mod. difficult	— Al	Brittle joint. Max use temp ~ 500 F Brittle joint. Max use temp ~ 500 F	↓
Steel	Other Metals (See STEELS)					
MAGNESIUM						
Magnesium	Steel	Arc weld	Mod. difficult	AZ92A, AZ61A	Pre-tin steel at joint area	Dow
NICKEL AND NICKEL-BASE ALLOYS						
Inconel	Austenitic Stainless	Tungsten arc	Easy	Inconel 62	Excellent ductility. Suited for high temp service	UCC Nuclear
	Carbon Steel	Shielded metal arc	Easy	Inconel 182	Excellent ductility	↓
	Molybdenum	Furnace braze	Mod. difficult	AMS-4777	Recommended for joining small sections	↓
	Nickel	Tungsten arc	Easy	Inconel 62	Excellent ductility. Used extensively for corrosion resistance	↓
	Platinum, Pt-10Rh	Brazing	Easy	60Pd-40Co	Braze in inert gas at 2300 F, use 0.002 in. fit up. Joint somewhat ductile	Boeing
	Tungsten	Furnace braze	Easy	Cu	Recommended for joining small sections. Used in high temp valves	UCC Nuclear
Inconel X	Molybdenum	Electron beam	Easy	—	Joint ductility equal to molybdenum	Hamilton-Standard
Nickel	Hastelloy N	Tungsten arc	Easy	Inconel 82	Excellent ductility Used for corr res	UCC Nuclear
	Stainless Steel	Projection weld	Easy	—	—	Fansteel Met.
Udimet 500	Inco 713	Electron beam	Easy	—	Joint ductility equiv to least ductile part	Hamilton-Standard
	Mo-0.5Ti	Braze	Easy	Sterling silver	Use inert gas brazing	Boeing
Waspaloy	Inco 100	Electron beam	Easy	—	Joint ductility equiv to least ductile part	Hamilton-Standard
	Inco 713	Electron beam	Easy	—	Joint ductility equiv to least ductile part	↓

Combination		Joining Method	Rel. Diff.	Filler	Other Comments	Source
PRECIOUS METALS						
Palladium	Austenitic Stainless	Electron beam	Easy	—	Joint ductility equiv to least ductile part	Hamilton-Standard
Silver	Titanium	TIG weld	Easy	Fine Ag	Forms braze type joint	Titanium Metals
REFRACTORY METALS						
Columbium	Austenitic Stainless	Furnace braze	Mod. difficult	45Ti-40Zr-15Fe	Experimental filler metal. Vacuum braze	UCC Nuclear
Molybdenum	Austenitic Stainless	Induction braze	Mod. difficult	Cu	For joining small sections. Special uses at 1000-1200 F	
	Graphite	Furnace braze	Easy	48Ti-48Zr-4Be; 35Au-35Ni-30Mo; 49Ti-49Cu-2Be	Special uses. Appears to have high temp capabilities. Last filler metal is experimental	
	Titanium	TIG weld Electron beam	Mod. difficult Easy	V intermed —	Joint has low ductility, is usable to 500 F Joint ductility equiv to least ductile part	Titanium Metals Hamilton-Standard
	Tungsten	Tungsten arc	Mod. difficult	Pt	Weld is brittle if W or Mo rod is used	UCC Nuclear
Mo-0.5Ti	AISI 4340, Ti-6Al-4V	Braze	Easy	Pd-40Co or sterling Ag	Use inert gas brazing	Boeing
Tantalum	Titanium	TIG weld	Mod. difficult	—	Joint relatively ductile	Titanium Metals
Tungsten	Steel	Resistance weld	Mod. difficult	Ni	Joint relatively brittle	Fansteel Met.
W, Ta, Cb, Mo	To Each Other	Braze	Easy	Ti-32V Ti-50Zr Ti-30Ta Ti-30Mo V-8Ta	Braze at 3200 F Braze at 3250 F Braze at 3450 F Braze at 3580 F Braze at 3575 F Joint ductility excellent if base metals are ductile as recrystallized, otherwise brittle. Use inert gas. Braze remelt temp raised 500 F	Boeing
STEELS						
Austenitic Stainless	Carbon Steel	Friction weld Thermatool	Easy Easy	— —	Excellent joint ductility Good joint ductility	AMF
	Ferritic Stainless	Shielded metal arc	Easy	Inconel 182	Excellent ductility. Suited for cyclic service up to 1050 F	UCC Nuclear
	Hastelloy N	Tungsten arc	Easy	Inconel 82	Excellent ductility. Good mech. props. at 1200 F	
	Low Alloy, High Strength Steels	TIG weld	Mod. difficult	19Cr-9Ni w/Mo	Good joint ductility. Str rel after welding	Republic Aviation
	Zircaloy-2	Friction weld Furnace braze	Easy Mod. difficult	— Zircaloy + 4% Be	Fair joint ductility Recommended only for small sections	AMF UCC Nuclear
	Martensitic Stainless	Electron beam	Easy	—	Good joint ductility. Str rel after welding	Hamilton-Standard
	Precip. Hard. Stainless	Electron beam	Easy	—	Joint ductility equiv to least ductile part	
	Titanium	Resistance spot	Easy	V intermed.	Joint has low ductility, is usable to 500 F	Titanium Metals
Ferritic Stainless	Titanium	TIG weld	Difficult	V intermed.	Joint has low ductility, is usable to 500 F	Titanium Metals
High Alloy	Low Alloy Steel	Friction weld	Easy	—	Excellent joint ductility	AMF
Martensitic Stainless	Precip. Hard. Stainless	Electron beam	Easy	—	Ductility equivalent to precip. hard. stainless-stress relieve joint	Hamilton-Standard
	Carbon Steel	Thermatool	Easy	—	Joint brittle, must be tempered	AMF
	Alloy Steel	Friction weld	Easy	—	Fair joint ductility	
Mild Steel	High Speed Steel	Thermatool	Easy	—	Joint brittle, must be tempered	AMF
	Martensi[illegible]inless	Thermatool	Easy	—	Good joint ductility	
	Titanium	TIG weld	Difficult	V intermed.	Joint has low ductility, is usable to 500 F	Titanium Metals
Stainless Steel	Carbon Steel	Tungsten arc	Easy	AISI 310 or 312	Ferritic or martensitic weld metal results; may have limited ductility	UCC Nuclear
Steel	Titanium	Electron beam	Easy	V	Joint ductility equiv to least ductile part	Hamilton-Standard
TITANIUM						
Titanium	Aluminum Oxide	Furnace braze	Difficult	49Ti-49Cu-2Be	Experimental filler metal. Use to join small sections	UCC Nuclear
	Vanadium	TIG weld	Mod. difficult	—	Joints relatively ductile	Titanium Metals

the steel surfaces are coated with a metal that is compatible with aluminum. Then, the workpieces are joined with an aluminum filler wire; a special welding technique is used to prevent damage to the coating. Complete details of this procedure and other procedures that have been used to join aluminum to steel are discussed later in this report.

Thus, unusual procedures must be used to fusion weld dissimilar metals that form compounds affecting the joint characteristics. However, undesirable intermetallic compounds may form even when methods other than fusion welding are used to join such metals as aluminum to steel, titanium to steel, titanium to copper, etc. When aluminum is brazed to steel, brittle intermetallic compounds form because of the reaction of iron with the molten aluminum filler metal. Such compounds also form as the result of the migration of iron and aluminum atoms during diffusion welding. However, the reactions that occur during brazing and diffusion welding are generally less severe than those that occur during fusion welding, and the degree of reaction or alloying can be more easily controlled by varying the brazing or diffusion-welding conditions. The formation of undesirable intermetallic compounds can be further minimized by (1) selecting the filler metal carefully, (2) using metal inserts that are compatible with the base metals, or (3) using barrier metals to limit diffusion. Of course, improvements in the properties of fusion-welded joints can be realized by using a process that produces a minimum-width weld bead or a welding technique that minimizes weld-metal dilution.

Most of the fusion-welding processes can be used to join dissimilar ferrous metals. However, because of the metallurgical consequences of the fusion process, only a few of these methods (gas tungsten-arc welding, electron-beam welding, and resistance spot and seam welding) have been used extensively to join other dissimilar-metal combinations. Dissimilar metals are most frequently joined by nonfusion joining methods.

Classification of Joining Processes

Metals are metallurgically joined by the application of heat, pressure, or a combination of heat and pressure. Over the years, a multitude of joining processes based on these principles have been developed; they are broadly classified as fusion joining processes and nonfusion joining processes. Complete descriptions of each process can be obtained in any standard welding handbook. However, since these terms are used extensively in this report, the two categories are discussed briefly to aid in differentiating between individual processes.

Fusion Joining Processes

The processes in which two metals to be joined are heated until they melt and fuse together are classified as fusion joining processes. The heat required for joining is generated by an electric arc, by a beam of electrons or photons, or by the resistance of the metals to the passage of an electric current. While pressure is essential in resistance welding, it is not required in other methods of fusion joining. The need for a filler metal is governed by the process requirements. The major fusion-welding processes are listed below according to the method of heat generation.

Arc	Beam
Shielded metal-arc	Electron beam
Gas tungsten-arc	Laser
Gas metal-arc	
Submerged-arc	
Electroslag	
Plasma	

Resistance

Spot
Seam
Flash
Upset

The following processes are used principally for welding similar and dissimilar ferrous metals: shielded metal-arc, submerged arc, electroslag, flash, and upset welding. They find little use in joining dissimilar nonferrous metals.

Nonfusion Joining Processes

The processes in which joining is produced without melting the base metals are classified as nonfusion joining processes. The solid-phase processes depend on pressure as the principal means to achieve joining; however, heat is often supplied or generated during the joining process. Joining can be accomplished without a filler metal. In contrast, the use of a filler metal that melts at a lower temperature than the base metals is a necessity for liquid-solid phase joining. With these processes the joint assembly is heated until the filler metal melts and flows between the joint surfaces; the joint is completed when the filler metal solidifies. All of the nonfusion processes listed below are used to join dissimilar metals.

Solid Phase

Diffusion welding
Pressure welding
Gas-pressure bonding
Cold deformation welding
Friction and inertia welding
Explosive welding
Ultrasonic welding

Liquid-Solid Phase

Soldering
Brazing

JOINING DISSIMILAR FERROUS METALS

More research has been devoted to the joining of dissimilar ferrous metals than to any other combination of metals; this is understandable because of the universal use of ferrous metals for structural purposes. Much of this research originated in the early 1920's when the trend toward more exacting operating conditions for heating equipment used in the generation of steam and the refining of crude oil required structural alloys with improved resistance to oxidation and corrosion. Prior to 1920, the low-carbon steels were able to meet the service requirements of such equipment. The newly developed ferritic and austenitic stainless steels were suitable for such facilities; however, because of their cost, these steels were used only for high-temperature sections of these installations. Low-carbon steels were used for the remaining sections. Because of the difficulty in producing sound, welded dissimilar-metal joints, the two grades of steel were connected by mechanical joints. In the early 1930's, the less highly alloyed chromium-molybdenum steels were developed for moderately high temperature service. Successful techniques were developed to weld these steels to low-carbon steels with the newly introduced consumable austenitic stainless steel electrodes. Since the chromium-molybdenum steels were weldable and cost less than the stainless steels, they were used extensively in the steam power plants and refinery equipment with excellent results. However, during the next two decades the service temperature of equipment used in steam plants and the rapidly expanding petrochemical industries increased gradually and improved structural materials were needed. It is now common practice to use the austenitic stainless steels for service temperatures in excess of 1050 F. Welded dissimilar-metal joints are used extensively to economize on material costs. For example, joints between low-carbon steel, chromium-molybdenum steel, and austenitic stainless steel may be encountered in steam superheaters. Since these early beginnings, the technology of joining dissimilar ferrous metals has kept pace with the service requirements of the expanding aerospace and nuclear industries.

Fusion Joining

Since the late 1940's, the literature is replete with references to research on the arc welding of dissimilar ferrous metals. While much of this research has been associated with the fabrication of piping joints for steam power plant services, it has been invaluable for other applications as well. The austenitic stainless steels can be welded to low-carbon or low-alloy steels if the electrode and welding technique are selected to prevent the occurrence of microfissuring, transition-zone cracking, carbon migration, and oxide penetration. The literature of the period reflects the preoccupation of the authors with these problems.

In 1947 Schaeffler discussed the selection of electrodes for welding dissimilar steels and developed a diagram that related the amount of ferrite in austenite to the composition of the electrode and the base metals.[7] This diagram, illustrated in Figure 1, is used in selecting electrodes to prevent extensive dilution of the weld metal by the base metals and the formation of a crack-sensitive microstructure. Much of the research is associated with the high-temperature behavior of austenitic-ferritic joints. In 1949 Weisburg discussed the results of cyclic-heating tests of austenitic-ferritic pipe joints for high-temperature steam service;[8] this was followed by an article by Stewart and Schreitz that discussed thermal-shock tests of austenitic-ferritic pipe joints.[9] In the early 1950's Carpenter, Jessen, Oberg, and Wylie discussed research on the arc welding of chromium-molybdenum steel to austenitic stainless steel for high-temperature, high-pressure service.[10] Fatigue tests and thermal-shock tests at elevated temperatures were conducted. Electrode selection and its relation to microfissuring was discussed along with the effect of carbon migration, accelerated oxidation, and stresses in the joint properties. Research on the problems of welding ferritic to austenitic steels for high-temperature service continued well into the mid-1960's with program results reported by Ronay and Clautice and by Tucker and Eberle.[11,12] A thorough study of the effects of carbon migration in austenitic-ferritic joints was conducted by Christoffel and Curran; the influence of time, temperature, and material composition on the extent of carbon migration was investigated with specimens that were fractured after treatment.[13] Under the test conditions used, carbon migration had little effect on the joint properties. Work of similar nature was undertaken by Livshits and Bakhrakh with different results.[14] Metallographic studies of the microstructures near the fusion line indicated that the hardness and brittleness of the martensitic structure increased because of carbon migration and the joint ductility was impaired. Gotal'skiy studied the high-temperature behavior of austenitic-ferritic joints that were welded with high-nickel filler metals; it was concluded that a mechanism other than carbon migration was responsible for premature joint failure, and further research was recommended.[15] In 1964 Slaughter and Housley discussed the evaluation of a new nickel-base electrode (Inconel 182) for welding ferritic to austenitic steels. These joints exhibited better resistance to cracking during thermal cycling than did similar joints that were welded with a Type 347 electrode.[16]

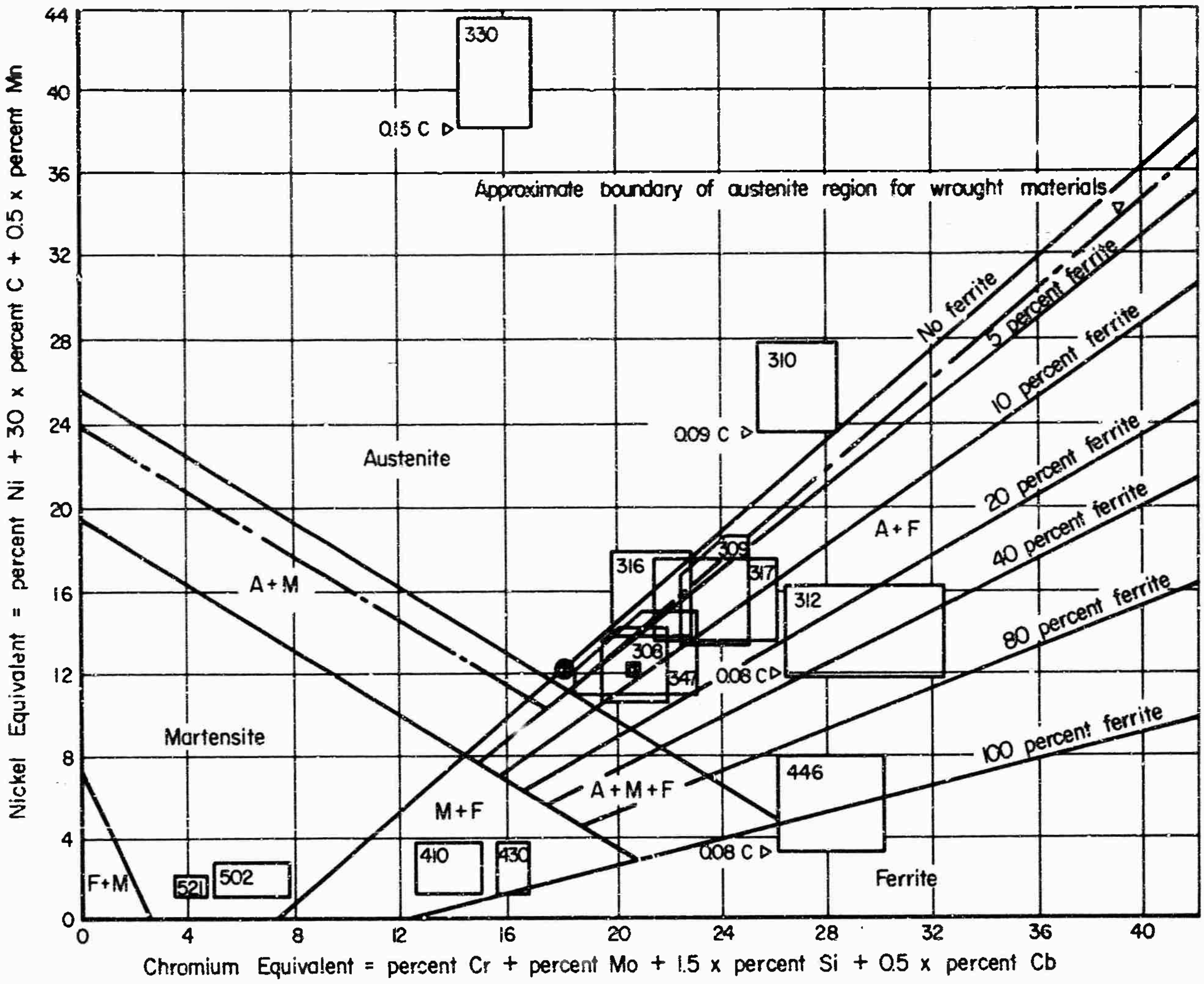


FIGURE 1. SCHAEFFLER'S DIAGRAM FOR THE MICROSTRUCTURE OF STAINLESS STEEL WELDS[21]

This brief review indicates the scope of the research conducted on the arc welding of dissimilar ferrous metals. More extensive summaries have been prepared by Rutherford and Thorneycroft; in these articles the problem areas are defined, and research on specific difficulties is reviewed.[17, 18] The American Welding Society has published an extensive bibliography on the welding of stainless steel; articles on welding stainless steels to other ferrous metals are included.[19] Other references are listed in the Bibliography section of this report.

Several of the conventional arc-welding processes, such as shielded metal-arc welding, gas metal-arc welding, and gas tungsten-arc welding, can be used to join the stainless steels to other ferrous metals. However, most dissimilar ferrous metal joints are welded with coated electrodes using the shielded metal-arc process, because of the nature of the joining operation (i. e., the fabrication of piping joints, the connection of pipes to valves and other fittings, etc.). The degree of difficulty experienced in producing acceptable joints is directly related to the difference in composition of the base metals. Two types of series-300 stainless steel can be readily welded; however, problems can be anticipated when a stainless steel is welded to a low-carbon or low-alloy steel. Such problems can be largely overcome by the proper selection of the filler metal, joint design, welding process, and welding technique. A thorough understanding of the metallurgical processes that occur during welding is also required.

The problems that arise from welding are associated with the mixing or alloying of the molten filler metal and the two base metals; depending on their compositions, brittle phases having inferior mechanical properties can occur in the weld metal. The degree of alloying is related to the arc penetration and the amount of metal melted during welding. Usually, there is less penetration and melting of the base metal with the shielded metal-arc or short-circuiting gas metal-arc processes than

with the other arc-welding processes. Penetration can be controlled by directing the arc toward the weld puddle rather than toward the unmelted base metal, by avoiding weaving techniques, and by using low arc currents. A V-groove joint design is usually used when the base-metal thickness is 0.750 inch or less; a U-groove is used for thicker sections.

The key to sound serviceable dissimilar-ferrous-metal welds lies in the selection of the filler metal. Proper selection is dependent on (1) the effect of base-metal dilution on the composition and properties of the weld metal and (2) the service conditions to which the joint will be subjected. Fully austenitic weld deposits tend to develop microcracks during welding. Since welds containing a small amount of ferrite are highly resistant to cracking, the filler metal is selected to form an austenitic weld deposit that contains a small amount of ferrite. When one of the base metals is highly austenitic, a filler metal that contains a large ferrite content, such as E312, can be used for welding to insure a weld deposit with sufficient ferrite to prevent cracking. Conversely, when one of the base metals is highly ferritic, it may be desirable to weld with a fully austenitic electrode, such as E310, to prevent the formation of a hardenable weld metal or a weld metal with an excessive content of ferrite. The Schaeffler diagram (Figure 1) is useful in predicting the microstructure of the weld deposit as a function of the electrode and base-metal compositions and the amount of dilution of the weld metal that occurs during welding.[7]

The Schaeffler diagram shows how the microstructure of the weld deposit is affected by those alloying elements in the stainless steel that act like nickel and those that act like chromium. The nickel equivalent group includes nickel, carbon, and manganese with an allowance being made for the nitrogen content of standard welds. The nickel equivalent is the ordinate of the diagram. The chromium equivalent group is the abscissa and includes the effects of chromium, molybdenum, silicon, and columbium.

To estimate the microstructure of a deposit, the nickel equivalent and the chromium equivalent are calculated from the composition, using the following formulas:

$$\text{Nickel equivalent} = \%\text{Ni} + 30 \times \%\text{C} + 0.5 \times \%\text{Mn}$$

$$\text{Chromium equivalent} = \%\text{Cr} + \%\text{Mo} + 1.5 \times \%\text{Si} + 0.5 \times \%\text{Cb}$$

The values obtained are marked off on the coordinates of the diagram, and, in this way, a point is located on the diagram. The microstructure shown at that point is the one predicted for a deposit of that composition. For example, a Type 302 stainless steel containing 0.10%C, 1.00%Mn, 0.5%Si, 17.5%Cr, and 8.5%Ni has a nickel equivalent of 12.0 and a chromium equivalent of 18.25. In the form of a weld deposit, its microstructure is shown by the closed circle on the diagram. The deposit just manages to be fully austenitic.

To continue this example, this steel is welded with a Type 308 electrode having a composition and a structure represented by the closed square. A tie line connecting the square and the circle indicates the structures of the welds that would result from the combination, at all possible degrees of dilution. For instance, the diagram shows that, if the weld metal is diluted to the extent of 50 percent with parent metal in the course of the welding operation, the deposit will contain about 5 percent ferrite. Normally, such a deposit should have satisfactory resistance to hot cracking and it would not have impaired impact properties at very low temperatures.

The example just given can be turned around. The stainless steel to be welded will be represented by the closed circle, and it is desired to produce a weld metal containing an average of 5 percent ferrite. If the extent of dilution is 50 percent, the weld metal will have the proper composition if a Type 308 electrode is used that has the composition corresponding to the closed square.

Many factors influence the extent to which the weld metal is diluted by melted parent metal during the welding operation. Among them are the welding process, joint design, metal thickness, number of passes, current setting, and travel rate.

The Schaeffler diagram can also be used to predict electrode compositions required to avoid ferrite or martensite in a stainless steel weld deposit. In addition, the diagram is helpful in estimating the trend of the microstructure developed when dissimilar steels are welded. An illustration of this situation is the welding of a stainless steel overlay on a piece of carbon steel chemical processing equipment. The carbon steel composition and the overlay composition can be marked on the diagram, and the tie line drawn between them will indicate the microstructures that may be encountered.

Base-metal dilution can also be controlled by "buttering" the joint surface of the low-carbon and low-alloy steel with a layer of stainless steel before the joint is welded. The composition of the electrode used for buttering is determined by the criteria discussed above; after buttering, the joint can be welded with a filler metal that is compatible with the stainless steel base metal. The compositions of deposited weld metal obtainable with some commercially available covered electrodes are shown in Table 2; the compositions of base filler metals for gas metal-arc welding and

TABLE 2. COMPOSITION AND MECHANICAL-PROPERTY REQUIREMENTS FOR COVERED STAINLESS STEEL ELECTRODES

AWS-ASTM Classification[a]	Composition of Deposited Weld Metal, percent[b] C	Cr	Ni	Mo	Cb + Ta	Mn	Si	P	S	Minimum Tensile Strength, psi	Minimum Elongation in 2 In., percent
E308	0.08	18.0 to 21.0	9.0 to 11.0	--	--	2.5	0.90	0.04	0.03	80,000	35
E308L	0.04	18.0 to 21.0	9.0 to 11.0	--	--	2.5	0.90	0.04	0.03	75,000	35
E309	0.15	22.0 to 25.0	12.0 to 14.0	--	--	2.5	0.90	0.04	0.03	80,000	35
E309Cb	0.12	22.0 to 25.0	12.0 to 14.0	--	0.70 to 1.00	2.5	0.90	0.04	0.03	80,000	30
E309Mo	0.12	22.0 to 25.0	12.0 to 14.0	2.0 to 3.0	--	2.5	0.90	0.04	0.03	80,000	35
E310	0.20	25.0 to 28.0	20.0 to 22.0	--	--	2.5	0.75	0.03	0.03	80,000	30
E310Cb	0.12	25.0 to 28.0	20.0 to 22.0	--	0.70 to 1.00	2.5	0.75	0.03	0.03	80,000	25
E310Mo	0.12	25.0 to 28.0	20.0 to 22.0	2.0 to 3.0	--	2.5	0.75	0.03	0.03	80,000	30
E312	0.15	28.0 to 32.0	8.0 to 10.5	--	--	2.5	0.90	0.04	0.03	95,000	22
E16-8-2	0.10	14.5 to 16.5	7.5 to 9.5	1.0 to 2.0	--	2.5	0.50	0.03	0.03	80,000	35
E316	0.08	17.0 to 20.0	11.0 to 14.0	2.0 to 2.5	--	2.5	0.90	0.04	0.03	80,000	30
E316L	0.04	17.0 to 20.0	11.0 to 14.0	2.0 to 2.5	--	2.5	0.90	0.04	0.03	75,000	30
E317	0.08	18.0 to 21.0	12.0 to 14.0	3.0 to 4.0	--	2.5	0.90	0.04	0.03	80,000	30
E318	0.08	17.0 to 20.0	11.0 to 14.0	2.0 to 2.5	6 x C min to 1.00 max	2.5	0.90	0.04	0.03	80,000	25
E330	0.25	14.0 to 17.0	33.0 to 37.0	--	--	2.5	0.90	0.04	0.03	75,000	25
E347[c]	0.08	18.0 to 21.0	9.0 to 11.0	--	8 x C min to 1.00 max[d]	2.5	0.90	0.04	0.03	80,000	30
E349[e]	0.13	18.0 to 21.0	8.0 to 10.0	0.35 to 0.65	0.75 to 1.2	2.5	0.90	0.04	0.03	100,000	25
E410	0.12	11.0 to 13.5	0.60	--	--	1.0	0.90	0.04	0.03	70,000[f]	20[f]
E430	0.10	15.0 to 18.0	0.60	--	--	1.0	0.90	0.04	0.03	70,000[g]	20[g]
E502	0.10	4.0 to 6.0	0.40	0.45 to 0.65	--	1.0	0.90	0.04	0.03	60,000[f]	20[f]
E505	0.10	8.0 to 10.5	0.40	0.85 to 1.20	--	1.0	0.90	0.04	0.03	60,000[f]	20[f]
E7Cr	0.10	6.0 to 8.0	0.40	0.45 to 0.65	--	1.0	0.90	0.04	0.03	60,000[f]	20[f]

(a) The Specification for Corrosion-Resisting Chromium and Chromium-Nickel Steel Covered Electrodes (AWS A5.4-62T, ASTM A298-62T) contains the complete requirements.
(b) Single values are maximums, except where specified.
(c) Minimum chromium shall be 1.9 x Ni, when specified.
(d) When specified, 0.10 Ta max.
(e) 0.15 Ti max, 1.25 to 1.75 W.
(f) Specimen heat treated at 1550 to 1600 F for 2 hours, furnace cooled at less than 100 F per hour to 1100 F, air cooled.
(g) Specimen heat treated at 1400 to 1450 F for 4 hours, furnace cooled at less than 100 F per hour to 1100 F, air cooled.

gas tungsten-arc welding are similar to those of covered electrodes.[20] The electrodes recommended for welding various types of stainless steel to carbon steel and two typical low-alloy steels are shown in Table 3.

Also to be considered in the welding of stainless steels to low-alloy steels for high-temperature service are the problems occasioned by (1) carbon migration and (2) the stresses in the joint resulting from the differences in the coefficients of expansion for the base metals and the filler metal. Carbon migration occurs when a carbon activity gradient is produced by a difference in alloy content of the base metals. The carbon will migrate across the fusion line from the low-alloy steel to the high-alloy steel; the degree of migration is dependent on the service

TABLE 3. COVERED ELECTRODES RECOMMENDED FOR WELDS BETWEEN STAINLESS, HEAT RESISTING AND CARBON STEELS

Base → Metals ↓	Alternative Electrodes and Procedures: Carbon Steel	1-1/4Cr-1/2Mo	2-1/4Cr-1Mo
201	(c);E309	(c);E309	(c);E309
202	(c);E309	(c);E309	(c);E309
301	(c);E309	(c);E309	(c);E309
302	(c);E309	(c);E309	(c);E309
302B	(c);E309	(c);E309	(c);E309
303(a)	(e);E309	(e);E309	(e);E309
304	(c);E309	(c);E309	(c);E309
304L	(c);E309	(c);E309	(c);E309
305	(c);E309	(c);E309	(c);E309
308	(c);E309	(c);E309	(c);E309
309	(c);E309;(d)	(c);E309;(d)	(c);E309;(d)
309S	(c);E309;(d)	(c);E309;(d)	(c);E309;(d)
310	E310;(d)	E310;(d)	E310;(d)
310S	E310;(d)	E310;(d)	E310;(d)
314	(c);E309;(d)	(c);E309;(d)	(c);E309;(d)
316	(c);E309;(d)	(c);E309;(d)	(c);E309;(d)
316L	(c);E309;(d)	(c);E309;(d)	(c);E309;(d)
317	(c);E309;(d)	(c);E309;(d)	(c);E309;(d)
317L(b)	(c);E309;(d)	(c);E309;(d)	(c);E309;(d)
321	(c);E309;(d)	(c);E309;(d)	(c);E309;(d)
330(b)	(e);E312;(d)	(e);E312;(d)	(e);E312;(d)
347	(e);E312;(d)	(e);E312;(d)	(e);E312;(d)
348	(e);E312;(d)	(e);E312;(d)	(e);E312;(d)
403	(g);(f)	(h);(f)	(i);(f)
405	(g);(f)	(h);(f)	(i);(f)
410	(g);(f)	(h);(f)	(i);(f)
414	(g);(f)	(h);(f)	(i);(f)
416(a)	E309	E309	E309
420	(g);(f)	(h);(f)	(i);(f)
430	(g);(f)	(h);(f)	(i);(f)
430F(a)	E309	E309	E309
431	(g);(f)	(h);(f)	(i);(f)
440A	(g);(f)	(h);(f)	(i);(f)
440B	(g);(f)	(h);(f)	(i);(f)
440C	(g);(f)	(h);(f)	(i);(f)
446	(g);(f);(d)	(h);(f);(d)	(i);(f);(d)
501	(g);(f)	(h);(f)	(i);(f)
502	(g);(f)	(h);(f)	(i);(f)
505	(g);(f)	(h);(f)	(i);(f)
Carbon steel	(g)	(j)	(j)
1-1/4Cr-1/2Mo		(h)	(h)
2-1/4Cr-1Mo			(i)

(a) Includes selenium-bearing grade, although welding usually is not recommended for any of the free-machining steels when high quality joints are required.
(b) Not a standard AISI grade designation.
(c) Butter chromium steel with E309; complete joint with E308.
(d) ENiCrFe-3 preferred, especially for joints for high temperature service.
(e) Butter chromium steel with E309, and chromium-nickel steel with E312; complete joint with E308.
(f) E309 or E310 may be used when matching composition weld metal is not required.
(g) Any E60XX or E70XX mild steel electrode.
(h) E8015-B2L, E8016-B2, or E8018-B2 (low alloy steel electrodes).
(i) E9015-B3L, E9015-B3, E9016-B3, or E9018-B3 (low alloy steel electrodes).
(j) E7015, E7016, E7018, or E7028 (mild steel electrodes).

temperature, the time of exposure, and the amount of carbide-forming elements contained in the high-alloy steel. Carbon migration produces a decarburized band on the low-alloy side of the fusion line; the joint properties are reduced by the presence of this band. With dissimilar ferrous metal joints, the effects of thermal cycling on the joint properties must be considered. When a joint between stainless steel and low-carbon or low-alloy steel is heated to a high temperature, stresses will be produced because of the differences in the expansion coefficients of the base metals; joint failure can occur if the joint is heated and cooled repeatedly in service. However, successful joints for this type of service have been fabricated with the copper nickel E4NIA electrode; the weld metal produced with such an electrode has sufficient ductility to overcome the stresses that occur during thermal cycling.

The heat treatment of dissimilar-ferrous-metal joints presents many difficulties. The ferritic base metal and transition zone have a high hardenability and localized stresses are retained after welding. An annealing treatment at 1250-1350 F is required to restore joint ductility. However, this treatment may sensitize the austenite and produce a microstructure that is susceptible to corrosion. If the joint is heated to about 1900 F, a temperature that is normal for annealing stainless steel, carbon migration will occur and the ferrite will transform to austenite. A reasonable compromise is to anneal at 1300 F for about an hour. (17) More serious problems are presented when the precipitation-hardening stainless steels are joined to other ferrous metals, and heat treatments should be carefully selected to maintain the required joint properties.

The resistance flash-welding process has also been used to fabricate dissimilar-ferrous-metal joints, particularly tubing or pipe joints. The pipe ends must be machined and carefully matched at the forging surfaces. Also, the input energy must be controlled and flashing must be held to a minimum, since the base metals have different burn-off rates.

Nonfusion Joining

The most commonly used nonfusion method of joining dissimilar ferrous metals is brazing. This process is particularly attractive for joining the stainless steels to low-carbon or low-alloy steels, because the base metals are not melted during joining; consequently, the problems associated with dilution are minimal. However, a number of factors to be discussed below must be considered in joining these materials.

The selection of the filler metal, brazing procedures, and required equipment is largely

governed by the type of steels being joined and the expected service conditions. Both the chromium-nickel and the hardenable chromium stainless steels can be readily brazed to less highly alloyed steels; however, in the brazing of the hardenable chromium alloys, the effects of the brazing cycle on the base metal must be considered. If the brazing temperature is below the hardening temperature, some loss in strength may occur. Sometimes brazing and hardening can be combined in a single operation, if the brazing temperature exceeds the hardening temperature. The brazing alloys should be selected with these considerations in mind. When the austenitic stainless steels are joined to other grades of steel, prolonged exposure to temperatures of 900 - 1300 F should be avoided if the joint is to be used in a corrosive environment. Under such conditions, carbide precipitation can reduce the corrosion resistance of the joint. Carbide precipitation can be minimized by:

(1) Selecting a brazing filler metal with a melting temperature higher than 1300 F

(2) Minimizing the brazing time if the filler metal melts in the critical range

(3) Using a brazing process that permits rapid heating and cooling of the joint

(4) Using a stabilized or extra-low-carbon grade of stainless steel

(5) Heat treating the joint to redissolve the carbides.

The austenitic stainless steels are also susceptible to stress-corrosion cracking, the result of base-metal attack by molten filler metals. To minimize the occurrence of such defects, the joints should be brazed in a stress-free condition.

The selection of filler metals for brazing dissimilar ferrous metals is based on the service conditions to which the joint will be subjected. The joint must possess the strength, oxidation resistance, and corrosion resistance to meet the service requirements. The strength and oxidation resistance of joints brazed with the copper- or silver-base alloys decreases rapidly above 500 and 800 F, respectively. However, since the stainless steels are not brazed to low-carbon steels for service under such conditions, these filler metals are suitable for most applications. If a stainless steel must be joined to a low-alloy steel for high-temperature service, the copper-manganese or gold-base filler metals can be used to produce joints that are serviceable up to about 1000 F; for higher temperature service up to 2000 F the nickel-base filler metals can be used. Filler metals that can be used to braze dissimilar ferrous metals are shown in Table 4.[21] The compositions of these alloys are covered by AWS-ASTM specifications; however, numerous other filler metals are available for use also.

The stainless steels must be carefully cleaned before brazing to remove traces of dirt, grease, and other surface contaminants; these can usually be removed by solvent cleaning. More vigorous cleaning methods, such as wire brushing or acid pickling, are needed to remove surface oxides. Fluxes or protective atmospheres must be used during brazing to prevent the formation of oxides that inhibit the melting and flow properties of the filler metals. Fluxes provide adequate protection when brazing is done at temperatures below about 1400 F with silver- or copper-base alloys. Inert or reducing atmospheres must be used at higher temperatures. An atmosphere of hydrogen is particularly useful, since it reduces chromium oxides at elevated temperatures, provided the dew point of the gas is low enough. Figure 2 can be used to determine the dew point-temperature relationship for the reduction of oxides in a hydrogen atmosphere.[21]

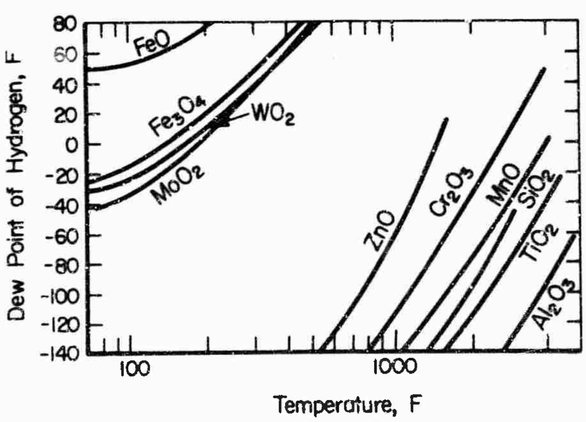


FIGURE 2. METAL--METAL OXIDE EQUILIBRIA IN HYDROGEN ATMOSPHERE

Each curve represents an equilibrium of metal and metal oxide. For points lying above or left of the curve, the oxide tends to form. Below or right of the curve, oxides tend to be reduced. Thus, at higher temperatures, more water vapor may be tolerated, or for a given dew point, prevention of oxidation is favored. When the metal is alloyed, a higher dew point may be tolerated than is indicated here, this diagram being based on pure metal.[21]

TABLE 4. BRAZING FILLER METALS[a] (21)

Filler Metal Classification	Cu	Ag	P	Zn	Cd	Au	Ni	Cr	Si	B	Other	Solidus (Temperature, F)	Liquidus (Temperature, F)
	Nominal Composition, percent												
BCuP-1	95	....	5	....	..	....	....	..	....	...	....	1310	1650
-2	92.75	....	7.25	....	..	....	....	..	....	...	....	1310	1460
-3	89	5	6	....	..	....	....	..	....	...	....	1190	1485
-4	86.75	6	7.25	....	..	....	....	..	....	...	....	1190	1335
-5	80	15	5	....	..	....	....	..	....	...	....	1190	1475
BAg-1	15	45	....	16	24	....	....	..	....	...	....	1125	1145
-1a	15.5	50	....	16.5	18	....	....	..	....	...	....	1160	1175
-2	26	35	....	21	18	....	....	..	....	...	....	1125	1295
-3	15.5	50	....	15.5	16	....	3	..	....	...	....	1170	1270
-4	30	40	....	28	..	....	2	..	....	...	....	1240	1435
-5	30	45	....	25	..	....	....	..	....	...	....	1250	1370
-6	34	50	....	16	..	....	....	..	....	...	....	1270	1425
-7	22	56	....	17	..	....	....	..	....	...	Sn-5	1145	1205
-8	28	72	....	....	..	....	....	..	....	...	....	1435	1435
-8a	27.8	72	....	....	..	....	....	..	....	...	Li-0.2	1410	1410
-13	40	54	....	5	..	....	1	..	....	...	....	1325	1575
-18	30	60	....	....	..	....	....	..	....	...	Sn-10	1115	1325
-19	7.3	92.5	....	....	..	....	....	..	....	...	Li-0.2	1435	1635
BAu-1	62.5	....	....	....	..	37.5	....	..	....	...	....	1815	1860
-2	20	....	....	....	..	80	....	..	....	...	....	1635	1635
-3	62	....	....	....	..	35	3	..	....	...	....	1785	1885
-4	.....	....	....	....	..	82	18	..	....		....	1740	1740
BCu-1	99.90 min.	....	....	....	..	....	....	..	....	...	....	1980	1980
-1a	99 min.	....	....	....	..	....	....	..	....	...	....	1980	1980
-2	86.5 min.	....	....	....	..	....	....	..	....	...	....	1980	1980
RBCuZn-A	59.25	....	....	40	..	....	....	..	....	...	Sn-0.75	1630	1650
-D	48	....	....	42	..	....	10	..	....	...	....	1690	1715
BNi-1	.....	....	....	....	..	....	73.25	14	4	3.5	Fe-4.5, C-0.75	1790	1900
-2	.....	....	....	....	..	....	82.4	7	4.5	3.1	Fe-3	1780	1830
-3	.....	....	....	....	..	....	90.9	..	4.5	3.1	Fe-1.5 max.	1800	1900
-4	.....	....	....	....	..	....	93.4	..	3.5	1.6	Fe-1.5 max.	1800	1950
-5	.....	....	....	....	..	....	70.9	19	10.1	...	....	1975	2075
-6	.....	....	11	....	..	....	89	..	....	...	....	1610	1610
-7	.....	....	10	....	..	....	77	13	....	...	....	1630	1630

(a) Values shown in this table should not be used for purposes of specification. Reference should be made to AWS A5.8.

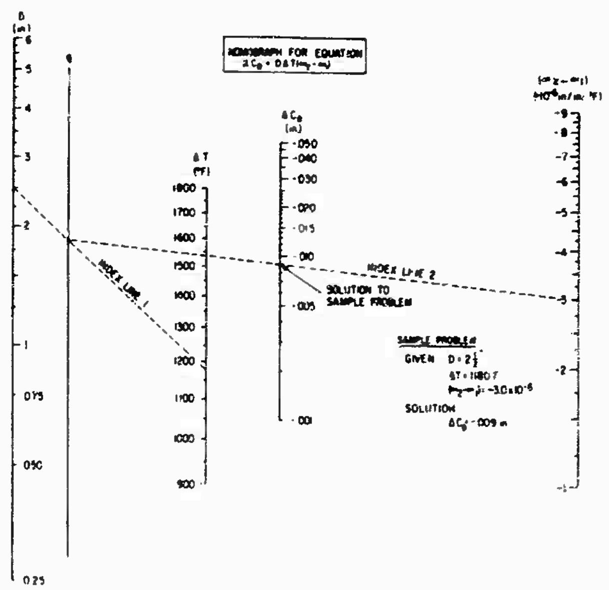
Special care must be exercised in joining the precipitation-hardening stainless steels to other ferrous metals. These alloys usually contain small percentages of aluminum and/or titanium. Since the oxides of these alloys cannot be reduced at practical brazing temperatures, joints involving them should be brazed in a vacuum.

Joint design is very important in brazing dissimilar ferrous metals, because of the differences in the coefficients of expansion of ferrous microstructures. Joint design must account for the expansion and contraction that occur during the heating and cooling portions of the brazing cycle; otherwise, cracking will occur in the joint area. The nomograph, Figure 3, can be used as a guide in designing joints for all types of dissimilar-metal joining.[22]

Friction welding has been used successfully to make dissimilar-ferrous-metal joints when one or more of the joint members can be rotated. Although this is not a new process, most of the exploitation of friction welding in the United States has occurred in the past 10 years. It is in direct competition with flash welding as a method to join similar and dissimilar ferrous metals. Hollander, Cheng, and Wyman investigated the parameters associated with the joining of Type 304 stainless steel to AISI 4140 steel.[23] Using 3/8-inch-diameter rods, it was found that joints with optimum properties were produced under the following conditions: (1) rotational speed- 3600 rpm, (2) heating pressure - 5000 psi, (3) heating time - 10 seconds, and (4) forging pressure - 20,000 to 30,000 psi. Data of a similar nature are discussed by Vill'.[24]

Significant developments in explosive welding as a method to join dissimilar ferrous metals have been made. However, most of this research has been directed toward cladding applications, eg., the cladding of low-carbon or low-alloy steel plate with a thin layer of corrosion-resistant stainless steel for use by the chemical industry. Explosive welding procedures have also been used to clad steel tubing. A recent publication summarizing the current status

of explosive welding indicated that many of the 200-, 300-, and 400-series stainless steels have been explosive welded to a variety of low-carbon, medium-carbon, and low-alloy steels.[25] This publication discusses (1) the mechanics of the explosive-welding process, (2) the types of available explosives, (3) the care and handling of explosives, (4) the evaluation of explosive-welded joints, and (5) numerous applications. The mechanical properties of explosive-welded dissimilar-ferrous-metal joints are discussed in detail by Demaris and Pocalyko.[26] Research to join stainless steel tubing to mild steel header plates has been conducted by Crossland, et al.[27] Several tube-to-header plate joint designs were evaluated during this study. An explosive with a low detonation velocity produced optimum joining of 1-inch-diameter tubing; the header plate thickness was 2 inches.



NOTES: (1) This nomograph gives change in diameter caused by heating. Clearance to promote brazing filler metal flow must be provided at brazing temperature.

(2) D = nominal diameter of joint, inches
C_D = change in clearance, inches
T = brazing temperature minus room temperature °F
α_1 = mean coefficient of thermal expansion, male member, in./in./°F
α_2 = mean coefficient of thermal expansion, female member, in./in./°F

(3) This nomograph assumes a case where α_1 exceeds α_2, so that scale value for $(\alpha_2 - \alpha_1)$ is negative. Resultant values for ΔC_D are therefore also negative, signifying that the joint gap reduces upon heating. Where $(\alpha_2 - \alpha_1)$ is positive, values of ΔC_D are read as positive, signifying enlargement of the joint gap upon heating.

FIGURE 3. Nomograph for finding the change in diametral clearance in joints of dissimilar metals for a variety of brazing situations.[22]
(Reproduced by Permission of American Welding Society)

The stainless steels can be joined to low-carbon or low-alloy steels by other nonfusion joining techniques, such as ultrasonic or diffusion welding. However, there is little reason to do so on a production basis, because other methods are adequate. Type 430 stainless steel was ultrasonically welded to a low-carbon steel during the course of a study of the fundamental nature of ultrasonic welding.[28] The base-metal thicknesses were 0.0005 inch for the low-carbon steel and 0.008 inch for the stainless steel. Similarly, Type 304 stainless steel was diffusion welded to three low-alloy steels during a program to study the migration of carbon in dissimilar-ferrous-metal joints.[29]

JOINING NONFERROUS METALS TO FERROUS METALS

Joints between ferrous and nonferrous metals are of interest to industry because they combine the strength and toughness of steel with the special properties, such as oxidation resistance, corrosion resistance, etc., provided by the nonferrous metal. The joining of ferrous to nonferrous metals is far more complicated than the joining of dissimilar ferrous metals, because of the wider variation in the physical, mechanical, and metallurgical properties of the metals being joined. The extent of these property differences is an excellent indication of the difficulty to be anticipated in joining such metals.

Aluminum to Steel

Joints of aluminum to various types of steel are useful because they combine the lightness, corrosion resistance, and good thermal and electrical conductivities of aluminum with the strength and durability of steel. Most of the research on joining aluminum to dissimilar metals has been concentrated on aluminum-to-steel joints. The fusion-welding processes that have been used most successfully in fabricating such joints include gas tungsten-arc welding and resistance spot welding; in addition, most of the nonfusion joining processes have been useful in joining these metals.

Fusion Joining

Aluminum cannot be joined directly to steel by gas tungsten-arc welding for reasons discussed below:

(1) Because of the wide difference in the melting temperatures of aluminum (1220 F) and steel (2800 F), aluminum will be molten and fluid before iron is well heated.

(2) Thermal stresses of considerable magnitude will be produced during the welding operation because of the difference in the coefficients of linear expansion, thermal conductivities, and specific heats of aluminum and steel.

(3) According to the aluminum-iron phase diagram, these metals form solutions, intermetallic compounds, and a eutectic. When the iron content of an aluminum-iron alloy exceeds 40 percent, a number of complex, brittle intermetallics such as $FeAl_3$, Fe_2Al_5, $FeAl_2$, FeAl, and Fe_2Al_7 may be formed. Ryabov and Duplyak have studied the reaction of molten aluminum with solid iron and have calculated the free energies of the intermetallic compounds.(30) During this reaction, a complex layer consisting primarily of $FeAl_3$ and Fe_2Al_5 forms at the joint interface. Iron-aluminum alloys containing more than 12 percent iron have little or no ductility.

The problems associated with fusion welding aluminum to steel have been overcome by (1) coating the steel surface with a metal that is compatible with aluminum or (2) using an aluminum-steel transition section that is fabricated by another joining method.

The use of metal coatings to minimize or prevent the formation of brittle intermetallic compounds during the arc welding of aluminum-to-steel joints dates back to the mid-1950's. Using the argon-shielded gas tungsten-arc process, acceptable tubing joints between Type 3004 aluminum alloy and aluminum-coated Type 304 stainless steel were produced by Miller and Mason.(31) During welding, the arc was directed toward the aluminum surface to prevent damage to the protective coating on the stainless steel; when the aluminum melted, the molten metal flowed and wet the coated-steel surface. The principles developed during this investigation are still in use today.

The usefulness of several metal coatings was investigated by Rabkin and Ryabov.(32) Aluminum-magnesium alloys were welded to low-carbon steel that was coated with each of the following metals: copper, nickel, cadmium, tin, lead, zinc, brass, magnesium, silver, and aluminum. Electrodeposited or hot-dipped coatings of tin, zinc, aluminum, silver, or their compounds were most effective in the production of sound joints. Regardless of the manner in which the coating was applied, tests indicated that the coating thickness should not exceed 40 to 50 μ.(32, 33)

Extensive studies to fusion weld aluminum to mild steel were conducted by Andrews.(34-36) Commercially pure aluminum, Al-1.25Mn, Al-3.5Mg, and an Al-Mg-Mn-Si alloy were argon-arc welded to mild steel that was coated with aluminum, zinc, or tin by hot-dipping or electroplating procedures; an Al-5Si filler wire was used for welding. Butt welds in sheet stock and tubing were made readily; lap welds were made less successfully. With fillet welds, single or double weld beads were possible; a secondary flow of shielding gas was required to prevent oxidation of the coating opposite the side being welded. The mechanical properties of butt welds in 1/8-inch-thick plate were generally adequate; some variation in the results was attributable to the particular coating on the steel and the manner in which it was applied. Long-term thermal treatments of welded joints at elevated temperatures indicated that service temperatures should not exceed 300 C (572 F) for extended operation; at higher temperatures, a brittle layer of $FeAl_3$ formed as the result of diffusion of aluminum into the steel and the mechanical properties decreased. Optimum corrosion properties were obtained with joints between aluminum and aluminized steel.

Research to join aluminum and its alloys to low-carbon steel for shipbuilding applications was conducted by Bel'chuk.(37-38) The steel was prepared for welding by applying a thin layer of aluminum or zinc to the joint surfaces; then, several heavier layers of pure aluminum were deposited on the coated surface by gas tungsten-arc welding procedures. The effect of the welding conditions on the bead contour and the thickness of the intermetallic layer were investigated.(37) Later studies by Bel'chuk were concerned with the fatigue strength and resistance to explosive stresses of aluminum-to-steel joints.(38) For these studies Al-6Mg alloy was tungsten-arc welded to a low-carbon steel that was coated with a thin layer (40 μ) of zinc before welding. The endurance limit of the joints was equivalent to that of the aluminum base metal; at higher stress levels, the fatigue life was greatly affected by the contour of the weld bead, and fracture occurred in the weld. These results are in general agreement with those obtained by Andrews.(34-36) The resistance of these joints to explosion bulge stresses was fairly high; the resistance was dependent on the strength of the filler metal.

It is generally agreed that the strength of aluminum-to-steel joints is highly dependent on (1) the metal used to coat the steel prior to welding, (2) the thickness of the coating, and (3) the degree of adherence between the coating and the steel surfaces. Joint strength is also dependent on joint design, since this determines

the load-bearing area of the joint. Joint strengths of about 14 to 20 ksi have been reported for various aluminum alloys joined to zinc-coated, low-carbon steel; fracture usually occurred in the joint at or near the steel interface. The effect of joint design has been shown in studies conducted by Orysh, et al.[39] The strength of lap joints between Type 2024-T4 aluminum alloy and a silver-coated, low-carbon steel was 400 to 3100 psi; butt joints between the same base metals had strengths of 20,000 psi and higher.

Experimental evidence indicates the strength of joints between aluminum and steel can be improved by measures to (1) inhibit the formation of brittle intermetallic compounds and (2) improve the adherence of the coating to the steel surface.[32, 33] In studies to weld Al-1.25Mn and Al-6Mg aluminum alloys to a zinc-coated, low-carbon steel, Ryabov and Yumatova noted that additions of 3 to 5 percent silicon, copper, or zinc to the filler wire decreased the width of the intermetallic layer and increased the joint strength to about that of the base metal.[33, 40] In earlier work, Rabkin and Ryabov compared the strengths of aluminum alloys that were tungsten-arc welded to a low-carbon steel that was coated with zinc by various procedures.[32] The joint strength of Al-5Mg-0.2V welded to low-carbon steel increased from about 18 to 27 ksi when the zinc coating was electrodeposited over a flash coating of copper instead of being applied to the bare steel surface.

Research to fusion weld aluminum to stainless steel has also been conducted, and the work undertaken by Miller and Mason has already been discussed. Gorin investigated the tungsten-arc welding of Al-1.25Mn or Al-6Mg to Type 321 stainless steel in sheet stock thicknesses; joints between Al-6Mg and Type 321 stainless steel tubing were also studied.[41] Before welding, the stainless steel surfaces were degreased and pickled; then, a thin layer of aluminum was applied to the cleaned surfaces by hot-dipping procedures. Sheet and tubing joints were produced by argon-shielded gas tungsten-arc welding. The tensile strengths of the flat specimens were equivalent to those of the aluminum base metals, but the bend properties were very erratic. The joints were further evaluated by impact and fatigue tests. Similar research has also been conducted by Rabkin, Ryabov, and others.[33, 40] A Type 6061 aluminum alloy fitting was welded to Type 204 stainless steel tubing.[42] A flash coating of copper was deposited on the stainless steel surface; then, the tubing was aluminized by hot-dipping. The assembled joint was tungsten-arc welded with Alcoa No. 716 filler wire.

The arc welding of aluminum-to-steel joints with the aid of transition sections has also been investigated. The transition sections consist of short lengths of aluminum and steel that are joined by pressure welding, friction welding, explosive welding, or other nonfusion joining processes. The transition sections are positioned between the aluminum and steel workpieces and welded by conventional procedures. Since welds are made between aluminum and aluminum or steel and steel, the problems associated with the formation of brittle intermetallic compounds are eliminated. Transition sections are available in plate or tubing form. Gorin evaluated the use of transition sections for joining Al-1.25Mn or Al-6Mg aluminum alloys to Type 321 stainless steel.[41] Clad metal sections produced by roll welding were used to join sections of sheet stock. The aluminum-to-aluminum weld was made first using minimum arc currents; then, the steel-to-steel weld was made. Cruciform joints had strengths equal to those of the aluminum base metals. Tubing transition sections of Al-1.25Mn and Type 321 stainless steel were fabricated by friction welding and used to join lengths of aluminum and stainless steel tubing. The mechanical properties of the friction-welded joint were not affected by subsequent welding operations, provided the transition section was long enough to limit the temperature at the joint interface to 250 C (482 F) or below.

Procedures incorporating the use of an intermediate metal have been developed for the resistance spot welding of aluminum to ferrous metals. In 1946, Hess and Nippes investigated the spot welding of Type 3003 aluminum alloy to SAE 4140 steel sheet stock.[43] The steel surface was electroplated with various thicknesses (0 to 0.0005 inch) of tin, zinc, nickel, chromium, cadmium, copper, or silver. Spot-welding studies indicated that optimum joining occurred with silver-plated steel; sound, ductile joints were produced over a wide range of welding conditions. Joints made with tin- or zinc-plated steel were brittle, and the welding conditions had to be closely regulated to produce sound joints with steel that was coated with nickel, cadmium, or chromium. Very high welding currents had to be used to produce welds with copper-plated steel; the plating thickness and welding current had to be closely controlled to produce ductile joints.

Gas metal-arc spot welding procedures, also involving fusion, have been developed to join aluminum to steel.[44] The surfaces of the steel workpieces were aluminized or galvanized to permit wetting by the aluminum filler wire. Optimum corrosion resistance was obtained with aluminized steel.

Nonfusion Joining

Nonfusion joining processes have been used with considerable success to fabricate aluminum-to-steel joints, because the possibility of forming undesirable intermetallic compounds is reduced by the absence of fusion. If intermetallic compounds form because of diffusion of aluminum into steel, the thickness of the intermetallic layer is

less than that formed during fusion welding, and its effect on the joint properties is smaller.

Several techniques were developed to solder aluminum to stainless steel tubing by Smith and Rabb.[45] In one procedure, the surface of the aluminum tubing was copper-plated and then tinned with a 50Sn-50Pb soft solder. The stainless steel tubing was also tinned, inserted into the aluminum tubing, and fluxed; then, the joint was completed by sweating the parts together. Tinning the aluminum tubing was also accomplished by ultrasonic means or by abrasion. An intermediate sleeve of copper was also used to facilitate joining these metals. The copper sleeve was brazed to the stainless steel tubing. Then, the copper sleeve was inserted into the aluminum tubing and the joint was completed with an aluminum-zinc solder.

More extensive research on brazing aluminum to steel has been conducted. In 1959, procedures were developed to braze Type 3003 aluminum alloy to Type 321 stainless steel.[46] The stainless steel member was plated with titanium to prevent the formation of brittle intermetallic compounds. Commercial aluminum brazing alloys were used for joining. The minimum tensile-shear strength of the brazed joints was 8340 psi. In 1963, Orysh, et al., discussed the evaluation of two sets of brazed specimens.[39] Lap-shear specimens were prepared from 0.125-inch-thick sheets of Type 6061 aluminum alloy brazed to AISI 1010 steel with the BAlSi-4 filler metal; the average tensile-shear strength was 6500 psi. Similar specimens were made from 0.125-inch-thick sheets of Type 3003 aluminum alloy brazed to Type 347 stainless steel; the average tensile-shear strength for ten specimens was 9600 psi. Type 304 stainless steel tubing has been brazed to a Type 6061 aluminum alloy fitting with Alcoa No. 716 filler metal.[42] Before brazing, the stainless steel tubing was copper plated and aluminized.

Type 304 stainless steel tubing has been brazed to Type 6061 aluminum alloy tubing for the plumbing system of a large liquid-propellant launch vehicle.[47,48] Tubing joints up to 8 inches in diameter were fabricated by salt-bath brazing for use as transition sections between tubing or fittings made from Type 321 stainless steel and Type 6061 aluminum alloy. The steps in the joining operation are listed below:

(1) The stainless steel tubing is coated with electroless nickel and plated with tin to a thickness of 0.0001 to 0.0003 inch.

(2) The aluminum tubing is cleaned in a hot alkaline and mixed deoxidizer bath immediately before brazing.

(3) The parts are assembled in a telescoping-type joint with the aluminum tubing on the outside. Since the aluminum has a higher expansion coefficient than stainless steel, thermal stress in the joint are eliminated during brazing. The joint clearance is 0.001 to 0.004 inch for 0.250 to 1.000-inch-diameter tubing, 0.001 to 0.006 inch for 1.000 to 3.000-inch-diameter tubing, and 0.001 to 0.008 inch for 3.000 to 10.000-inch-diameter tubing.

(4) The brazing alloy, Alcoa No. 718 (Al-12Si) is preplaced in the joint.

(5) The joint assembly is preheated to a temperature of 400 to 900 F, depending on size, and salt-bath brazed. After brazing, the assembly is cleaned to remove traces of residual salt.

The mechanical properties of these aluminum-to-steel joints were determined by tests conducted at room temperature and -423 F; in addition, burst tests, vibration tests, and cryogenic thermal-shock tests were conducted. The joint strength was adequate for the intended application. Type 321 stainless steel has also been brazed to Type 6061 aluminum alloy using the procedures outlined above.

A program with the same objectives as the program discussed above was conducted to diffusion weld transition sections of Type 321 stainless steel and Type 2219 aluminum alloy.[49-51] It is not possible to dip-braze most of the 2000 series or the 7000 series of aluminum alloys with commercially available filler metals because the solidus of these systems usually is found at a lower temperature than that of the filler metals. However, earlier work had indicated the feasibility of diffusion welding aluminum to steel.[39,43,52] During the initial phases of this program, research was conducted to develop diffusion-welding techniques that could be used in the fabrication of a 20-inch-diameter (and ultimately, a 50-inch-diameter) transition section. It was determined that the diffusion welding of the aluminum-to-stainless steel joint could be done in air under the following conditions: (1) temperature-500 to 600 F, (2) pressure - 20 to 25 ksi, and (3) time - 2 to 4 hours. Silver was electrodeposited on the aluminum and stainless steel surfaces to promote diffusion. To insure proper adherence of the silver to these surfaces, a nickel strike and copper flash were used prior to silver plating the stainless steel, and a zincate treatment and copper flash were used prior to silver plating the aluminum. The joint properties were evaluated by metallurgical studies, mechanical tests, and corrosion tests. The joint design and tooling required for diffusion welding the 20-inch-diameter transition ring are shown in Figures 4 and 5; the basic concepts were confirmed by diffusion welding several 8-inch-diameter sections.

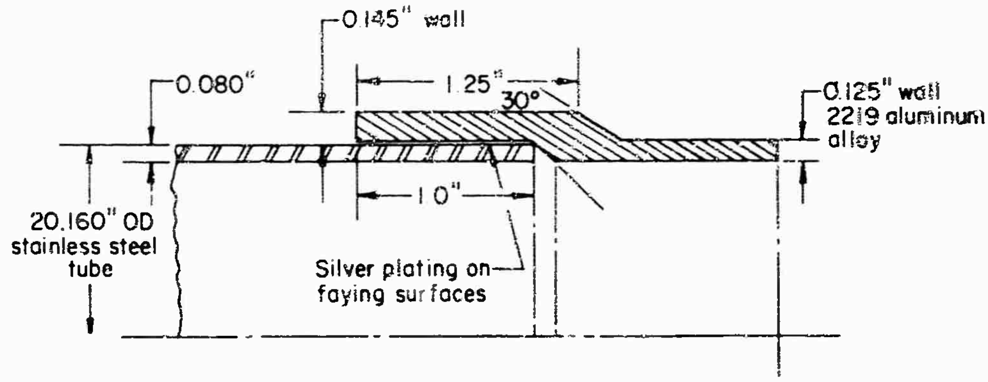


FIGURE 4. JOINT CONFIGURATION OF 20-INCH-DIAMETER TUBULAR WELD ASSEMBLY [49]

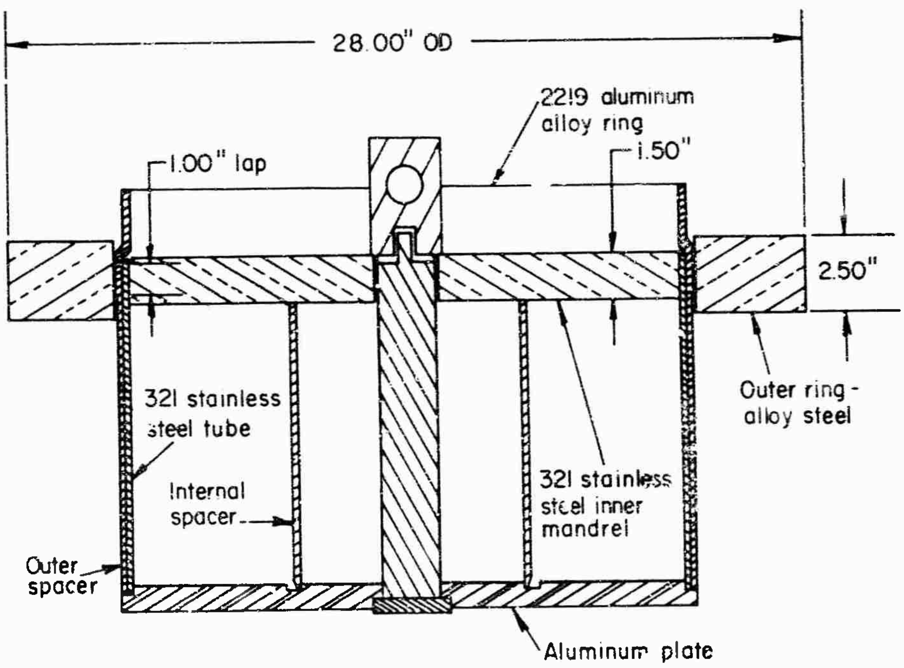


FIGURE 5. ARRANGEMENT OF PARTS AND TOOLING FOR WELDING 20-INCH-DIAMETER TUBULAR ASSEMBLIES [49]

Following welding, the joints were evaluated by helium-leak tests conducted before and after thermal-shock tests. Then, end covers were welded to the transition sections to form pressure vessels for pressure cycling and burst testing. The conditions under which the joint properties were evaluated and the test results are shown in Table 5. During burst testing of the first three assemblies, failure initiated in the diffusion-welded joint because of the application of a peel load during pressurization. The wall thickness of the aluminum ring was increased slightly and a fourth transition section was welded and tested; failure occurred in the circumferential weld at the end cover.

Diffusion-welded joints between Type 2219 aluminum alloy and Type 321 stainless steel were also made using the differential expansion tooling and joint design shown in Figures 6 and 7, respectively.[50] The external aluminum tubular member was cooled to -320 F and inserted into the die that was heated to 250 F. Then, the internal stainless steel member was inserted into the taper with a light pressure of 100 pounds. The joints were welded in air at a temperature of 500 F for 2 hours; the joint surfaces were silver plated to promote diffusion. After welding and removal from the die set, the tubing was machined to remove the outer reinforcement. After thermal-shock tests and helium-leak checks, the joints were tested in tension; the shear load required to produce failure was 7800 pounds. Fracture occurred in the aluminum base metal. Additional studies are being conducted with joints having diameters of 0.5, 2.0, 4.0, and 8.0 inches. The joints are being evaluated by thermal-shock tests, helium-leak tests, and various dynamic tests; the results to date are shown in Table 6.[52]

TABLE 5. SUMMARY OF 20-INCH-DIAMETER TANK TESTS[49]

Tank	Test Method	Cycle Pressure, lbs	Number Cycles	Burst Pressure, psi	Hoop[a] Stress, psi	Joint Shear Load, lb/in.	Failure Mode
1	Water (RT)	350	200	470	37,600	2350	Diffusion-welded joint
2	LN_2 (-320 F)	350	92	505	40,400	2520	Diffusion-welded joint
3	LN_2 (-320 F)	310 240	60 140	670	53,600	3350	Diffusion-welded joint
4	Water (RT)	240	100	645	51,600	3220	Circumferential weld at aluminum head
4 retest	LN_2 (-320 F)	--	--	695	55,600	3470	Circumferential weld at aluminum head

(a) Based on 0.125-inch-thick aluminum alloy tank shell.

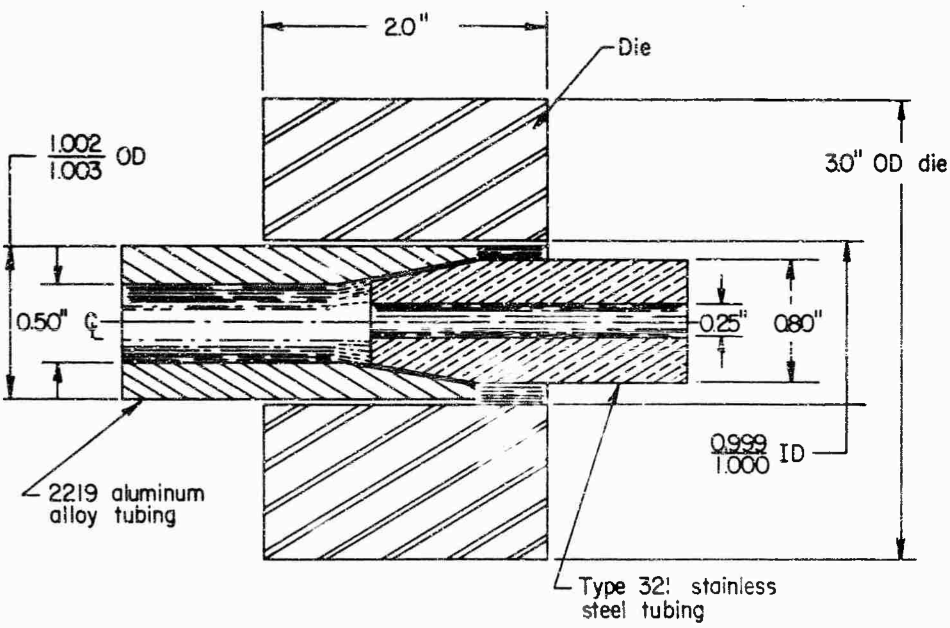


FIGURE 6. JOINT AND TOOLING ARRANGEMENT FOR DIFFUSION[50] WELDING DISSIMILAR-METAL TUBULAR ASSEMBLIES

Joints between aluminum and steel have been made by pressure welding, cold welding, or roll welding. All of these processes are related in that considerable pressure is required for joining; heat may or may not be required. In a review of the published literature, Ryabov indicated that aluminum could be cold welded to steel using deformation of 47 to 81 percent.[53] The tensile strengths of such joints ranged from about 12 to 14 ksi; the joint strength was increased to 24 ksi by annealing the joint at 930 F. Gritsenko, et al., cold welded cylindrical joints between Al-6Mg aluminum alloy and Type 321 stainless steel; the tensile strength of these joints was about 42 ksi.[54] The joining conditions were not presented however, different amounts of deformation were used for each of the base metals. The cold and pressure welding of these same alloys was also discussed by Shestakov.[55] The pressure welding of aluminum to stainless steel is described in a patent awarded to Dulin.[56] Using this technique, the workpieces are abrasively cleaned and placed between the platens of a hydraulic press at a pressure of 15 ksi. When the specimen temperature reaches 700 F, the pressure is increased rapidly to produce a deformation of 25 percent in the aluminum.

The roll welding of aluminum to iron was included in a study of the parameters associated with joining dissimilar metals.[57] Strong joints

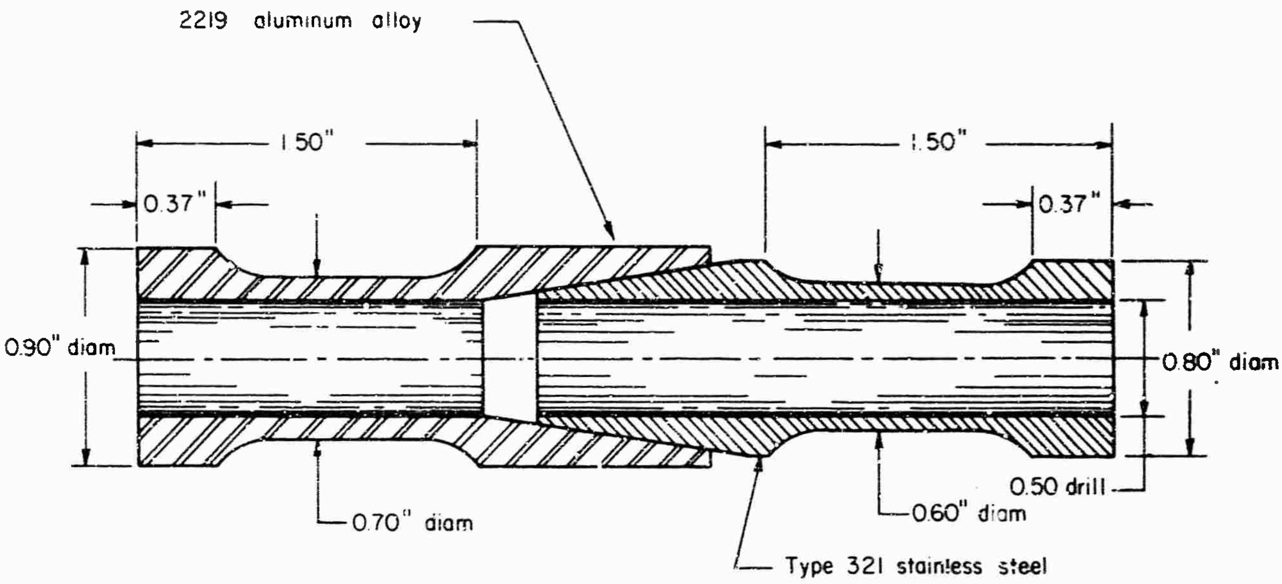


FIGURE 7. JOINT DESIGN FOR DIFFUSION WELDING DISSIMILAR-METAL TUBING (50)

TABLE 6. TESTING OF DIFFUSION-WELDED 2219 ALUMINUM ALLOY TO 321 STAINLESS STEEL TUBULAR JOINTS (52)*

Specimen	Joint Diameter, inches	Thermal Shock +180 F to -320 F	Helium Leak	Vibration: Random 27 G's RMS(a)	Vibration: Sinusoidal 5 G's	Helium Leak	Cyclic Pressure, psig: 72 F 200 Cycles,	Cyclic Pressure, psig: -320 F 200 Cycles,	Helium Leak	Burst Test, psig: 72 F	Burst Test, psig: -320 F,
A1	0.5	5 Times	x				4480				
A2	0.5	Ditto	x				4480				
A3	0.5	"	x								
A4	0.5	"	x								
A5	0.5	"	x								
A6	2.0	"	x	14.8 min (b)		x					
A7	2.0	"	x	6 min		x					
A8	2.0	"	x	15 min (b)	10^5 cycles	x	1920				
A9	2.0	"	x	15 min	10^5 cycles		1920				
A10		"	x								
A11											
A12											
A13											
A14	4.0	"	x				945				
A15	4.0	"	x				945				
A16	4.0	"	x								
A17	4.0	"	x								
A18	4.0	"	x								
A19	8.0	"	x								
A20	8.0	"	x								
A21	8.0	"	x								
A22	8.0	"	x								
A23	8.0	"	x								

(a) Test duratic[illegible] minutes.
(b) Failed [illegible] of specimen fitting.
* x indicates [illegible] completed, blank space indicates test to be completed.

were produced by roll welding; however, the strength declined rapidly when the joints were heated to a temperature at which diffusion of aluminum into iron occurred. A limited study to determine the feasibility of roll welding Types 2219 and 7106 aluminum alloy to Type 321 stainless steel was conducted by Crane, et al.[50] The joints had excellent peel strength and ductility when welded at 750 or 850 F; joints that were welded at 650 F had low peel strengths. There was no evidence of the formation of an intermediate phase at the bond line. The roll welding of aluminum-to-steel transition sections for use in joining aluminum and steel components was discussed by Razdui, Zasukha, and Ryabov.[58] Joints were made between the following aluminum and ferrous alloys: (1) Al-6Mg and Type 321 stainless steel, (2) Al-5Mg-0.2V and Type 321 stainless steel, (3) Al-6Mg and low-alloy steel, (4) Al-3Mg and low-alloy steel, and (5) Al-6Mg and low-carbon steel. After the aluminum and steel strip was cleaned by chemical and abrasive methods, the aluminum strips were heated to 662-842 F. Then, the aluminum and steel strips were assembled in a pack and rolled immediately; the reduction in thickness ranged from about 40 to 70 percent. The shear strength of these joints was about 10 to 13 ksi. Sections of steel 0.24 inch thick and aluminum 0.16 inch thick were arc-welded to these transition elements; the width of the steel and aluminum sections was 2 inches. These assemblies were tested in tension; the breaking loads varied from 2500 to 4000 pounds.

Friction welding is another method that can be used to join aluminum and steel without an intermediate metal. Commercially pure aluminum was friction welded to a low-carbon steel and Type 321 stainless steel without difficulty; however, joints with satisfactory mechanical properties could not be produced between steel and aluminum alloys that contained magnesium, copper, zinc, or silicon.[59-60] During friction welding of aluminum to low-carbon steel, temperature measurements in the joint area indicated that the aluminum almost reached its melting temperature; thus, diffusion rates were high and an interlayer containing brittle compounds (mainly $FeAl_3$) formed. Therefore, welding conditions that result in low heat inputs must be used to minimize the thickness of the intermetallic layer. Higher heat inputs can be used to friction weld aluminum to stainless steel, because the diffusion rates are not as high as those experienced with low-carbon steels. The tensile strength of friction welds between commercially pure aluminum and low-carbon or stainless steel was about 12 ksi. The operating temperature of aluminum to steel joints is limited by the diffusion rate of aluminum into iron. If the joint is subjected to a temperature at which a significant layer (10 μ or more) of brittle $FeAl_3$ forms by diffusion, the joint will lose its strength. Ginzburg, et al., recommended operating temperatures below 750 F for aluminum-stainless steel joints.[59]

An extensive investigation of the microstructures produced during the friction welding of aluminum to stainless steel was conducted by Scott and Squires.[61] As-welded friction welds were stronger than the aluminum base metal; however, the joint strength decreased rapidly at elevated temperatures. The joints were stable for (1) 18 months at 750 F, and (2) 13 months at 840 F. There was a noticeable increase in the width of the diffusion zone at 840 F. The authors stated that the joints were not stable at 1100 F for more than 15 minutes.

Friction welds between Type 6061 aluminum alloy and Type 304 stainless steel tubing were made for use as transition sections.[47] The average joint strength was 28.3 ksi; before testing, the joints were thermal cycled several times between 212 F and -320 F without any indication of failure. Joints between aluminum and steel have also been made by inertia welding, a variation of the friction-welding process in which the rotational energy is stored in a flywheel until metal-to-metal contact is made.[62]

In their report on explosive welding, Linse, Wittman, and Carlson indicate that aluminum and its alloys have been joined to most types of steels by this method.[25] For example, hemispherical configurations have been produced by explosively welding Type 2219 aluminum alloy to Type 301 stainless steel.[63]

Ultrasonic welding can be used to weld aluminum to steel without using an intermediate metal to promote joining. A large number of aluminum alloys and steels have been joined, but the base-metal thicknesses were small. Orysh, et al., joined the following materials: (1) 0.005-inch-thick Type 1100 aluminum to 0.016-inch-thick stainless steel (2) 0.04-inch-thick Type 3003 aluminum to 0.028-inch-thick AM-350 stainless steel, and (3) 0.031-inch-thick Type 6061 aluminum to 0.030-inch-thick Type 301 stainless steel.[39]

Titanium to Steel

Fusion Joining

With few exceptions the fusion joining processes are not considered suitable for the fabrication of titanium-to-steel joints. The same difficulties that are experienced in welding aluminum to steel (i.e., the differences between the physical and mechanical properties of the base metals, the metallurgical incompatibility of the base metals, etc.) are also encountered when titanium is joined to steel. The solubility of iron in α- titanium is very low, and if the concentration of iron exceeds about 0.1 percent, TiFe- and $TiFe_2$-type intermetallic compounds are formed. These compounds are very hard and brittle. Thus, if titanium is fusion welded to low-carbon or

low-alloy steel, the weld will have little or no ductility. The difficulties are increased if titanium is welded to stainless steel, because complex intermetallic compounds of titanium with iron, chromium, and nickel are formed. Fusion welding has been attempted with processes that produce minimum melting of the titanium; a filler metal that is compatible with titanium is used.

Research on arc-welding of titanium alloy Ti-3Al-1.5Mn to Type 321 stainless steel was conducted by Gurevich and Zamkov. [64] Unsuccessful attempts were made to join these alloys by a braze-welding technique; however, more successful joints were produced with the aid of an intermediate metal that was compatible with titanium and stainless steel. Experimental joints between titanium and stainless steel were produced with a vanadium insert by automatic gas tungsten-arc welding in a controlled-atmosphere chamber; these joints did not contain any defects but their ductilities were low. Joints were also made with a composite insert composed of tantalum and a high-copper alloy; the insert was positioned in the joint so that titanium was welded to tantalum and stainless steel was welded to copper. These joints had tensile strengths of about 70 to 80 ksi.

The gas tungsten-arc process has been used to join pure titanium to mild steel by a variation of the plug-welding technique. [65] Two procedures were used to weld 0.040-inch-thick titanium to 0.250-inch-thick steel. In the first case, a 9/16-inch-diameter hole, 1/16 inch deep, was drilled in the steel; this hole was filled with vanadium by gas tungsten-arc welding. Then, a 1/4-inch-diameter hole was drilled through the titanium sheet. The titanium sheet was positioned so the hole was located over the vanadium pad; then, the hole was filled with pure titanium by gas tungsten-arc welding. In the second procedure, a circular wafer of pure vanadium was placed in a countersunk hole in the steel and was welded in place. Then, the titanium was welded directly to the vanadium wafer. Molybdenum was also studied for use as an intermediate metal; however, it was considered to be inferior to vanadium because of the extreme hardness of the molybdenum-steel weld zone.

Resistance spot welding has been investigated as a method to join titanium to steel. In 1956 McBee, et al., studied the resistance spot welding of commercially pure titanium to Type 321 stainless steel. [66] Welds made at low heat-inputs were similar to solid-state welds; at increased heat inputs, an extremely brittle intermetallic phase was formed at the joint interface. Spot welds between titanium and the major constituents of stainless steel (iron, nickel, and chromium) were made; the titanium-to-chromium weld was better than either of the other two welds. However, there was little improvement in weld properties when chromium was used as an intermediate metal between titanium and stainless steel. Mitchell and Kessler demonstrated the feasibility of using vanadium as an intermediate metal between titanium and low-carbon or stainless steel; they were not successful in using aluminum or silver as intermediates. [65]

Titanium can be clad to ferrous metals by explosive welding, roll welding, and brazing. The problems associated with joining titanium-clad steel have been considered by Moore. [67] Methods to accomplish this are shown in Figure 8.

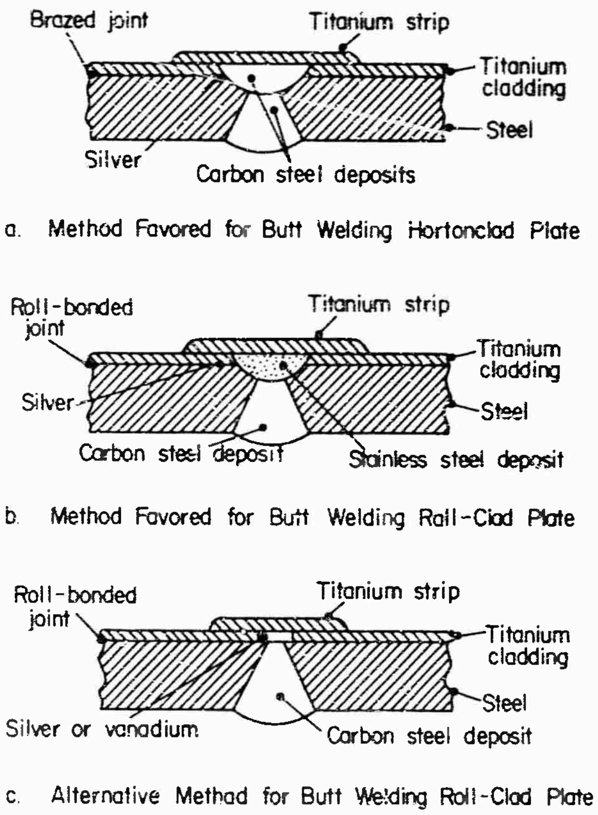


FIGURE 8. METHODS TO FUSION WELD TITANIUM-CLAD STEEL [67]

Nonfusion Joining

Brazing is used most frequently to join titanium to steels of various types. Most of the filler metals used for this purpose are based on silver or other noble metals. Silver-base alloys wet titanium and most steels well, and the reaction between them and titanium can be controlled quite readily.

The brazing of titanium to Type 321 stainless steel and 17-7PH precipitation-hardening stainless steel was discussed by Levy and Kaarlela, respectively. [68,69] Sleeve joints between titanium and Type 321 stainless steel were induction brazed in an argon atmosphere using a 98Ag-2Al filler metal. The results of joining appeared to be successful; however, the joints failed within 100 hours in salt-spray tests. The corrosion resistance of these joints was not

improved by plating the titanium surfaces with silver or the stainless steel surfaces with nickel. Additional work was conducted to determine the usefulness of some newly developed filler metals containing silver and aluminum as their major constituents. A sandwich structure consisting of 17-7 PH face sheets and a titanium core was brazed with an Ag-5Al-0.5 to 1.0 Mn alloy. These joints successfully withstood a 50-hour salt-spray test and a 100-hour oxidation test at 800 F.

A brazed transition section to be located between a titanium tank and stainless steel feed lines was evaluated during the course of the Gemini program.[70] Titanium alloy Ti-6Al-4V was vacuum-induction brazed to Type 304L stainless steel with the Au-18Ni filler metal. The presence of a brittle intermetallic compound and indication of cracking led to extended joint evaluations. Cracking could not be induced by two-point loading. Cracks were induced by cantilever loading the joint through the titanium member, but failure did not occur by continued bending. It was concluded that the brazed joint could sustain loads in excess of the yield strength of the stainless steel. The successful performance of this joint has been attributed to the rigid control of all the brazing process variables.[71] The joint clearances were held to very close tolerances and the joint was brazed rapidly; because of the rapid heating rate and a minimum holding time at temperature, the formation of brittle intermetallic compounds was minimized. The same procedures have been used to make joints between titanium and mild steel, Vascojet-1000, and other metals.

Alloy-development studies have been conducted to produce a brazing filler metal that could be used to join titanium to stainless steel for use in the Apollo plumbing system. In addition to the requirements that the melting temperature of the brazing filler metal be below the beta transus of the titanium alloy and that joining occur without the formation of brittle intermetallic phases, the joints had to be strong, leak-tight, and inert to nitrogen tetroxide. Also, the filler metal had to be exceptionally ductile, because the metal member with the larger coefficient of expansion (stainless steel) was positioned inside the member with the smaller coefficient of expansion (titanium); thus, the braze bond line was in tension. A palladium-base filler metal (Pd-14.3Ag-4.6Si) was developed for joining Ti-5Al-2.5Sn titanium alloy to Type 304L stainless steel.[72] However, further evaluation of this filler metal indicated that, while many of the joining criteria were satisfied, the alloy was sluggish and did not flow well.[73] Another filler metal, Ag-9.0Pd-[illegible] 2Si, was developed and evaluated. Plug-in-hole type joints were brazed at 1360 F in a vacuum of 3×10^{-5} torr. Excellent flow properties were exhibited by this alloy. Additional specimens were brazed and helium-leak checked before and after thermal cycling from room temperature to -320 F; the leak-rate requirements were satisfied. Further evaluation of this alloy is planned.

Other research on brazing titanium to steel has been undertaken. In 1958, the feasibility of brazing a steel bearing race (AISI 4340) to a C-130AM (Ti-4Al-4Mn) titanium-alloy propeller blade was investigated.[74] Sleeve joints were induction-brazed in an argon atmosphere with filler metals that flowed at 1000, 1250, 1450, and 1800 F. To promote flow of the brazing alloy, the steel member was plated with nickel. Joints brazed with pure silver or a silver-base alloy (Ag-15.5Cu-16.5Zn-18Cd) had acceptable properties for this application; the joint shear strengths were about 10 ksi. The use of aluminum or aluminum-base alloys for brazing titanium to steel is indicated by a patent issued to Harrick and Holzworth.[75] The joint members are hot-dip coated with aluminum, then assembled, and salt-bath brazed.

The use of eutectic diffusion brazing to join titanium to steel was investigated by Kharchenko.[76] Eutectic diffusion brazing combines the features of brazing and diffusion welding. An intermediate metal that forms a eutectic with one of the base metals is located between the workpieces; a foil or an electrodeposited coating can be used. Joining occurs when the assembly is heated above the eutectic temperature; a liquid phase may form, but it disappears by diffusing into the base metals. Cylindrical joint members (1/2 inch in diameter by 1 inch long) of a titanium alloy containing 3 percent aluminum and Type 321 stainless steel were assembled under light pressures and heated in a vacuum to a temperature slightly higher than that at which the titanium-nickel eutectic forms. The ultimate tensile strength of these joints was about 47 ksi at room temperature, 43 ksi at 1110 F, 40 ksi at 1300 F, and 30 ksi at 1470 F. A tapered tubing joint was fabricated by these procedures.

Diffusion welding has been used extensively to fabricate titanium-to-steel joints. In a review of the fundamentals of solid-state welding, Albom reported on the diffusion welding of titanium to stainless steel.[77] The process variables used for welding were not given; however, negligible pressure was required, similar to the work undertaken by Kharchenko. The photomicrograph of the joint indicated the presence of an intermetallic layer that was probably the nickel-titanium eutectic.

The diffusion welding of Ti-8Al-1Mo-1V titanium alloy to Type 321 stainless steel was investigated in the course of a program to develop procedures to fabricate transition sections for cryogenic tubing applications.[50,52] Joints were diffusion welded in air and in a vacuum using bare or electroplated base metals. Based on metallurgical studies, corrosion tests, and mechanical tests, the following conditions were

selected for diffusion welding: (1) bare base metals: 1425 ± 25 F for 10 minutes in a vacuum and (2) silver-plated base metals: 700 F for 30 minutes in air. The silver-plated specimens were pre-diffused at 1350 F for 10 minutes prior to welding. Tubular transition sections were prepared using the tooling and joint design shown in Figures 6 and 7. Helium-leak tests before and after thermal cycling from room temperature to -320 F indicated the soundness of these joints; the shear load to failure was 12,800 pounds. Failure occurred in the titanium-alloy tubing. In an extension of this program, joints between Ti-8A-1Mo-1V titanium alloy and Type 321 stainless steel are being diffusion welded to produce transition sections with diameters of 0.5, 2.0, 4.0, and 8.0 inches.[52] The joint properties are being evaluated by thermal-shock tests, helium-leak checks, vibration tests, cyclic pressure tests, and burst tests. The results to date are shown in Table 7.

anical and metallographic tests were conducted. The joint tensile strength was not affected significantly by the heat treatment; however, the joint ductility decreased rapidly due to the formation of brittle intermetallic compounds. The cold welding of titanium to steel joints was also investigated by Hughes.[80]

Joints of this type have been produced by ultrasonic welding. Joints were made between 0.024-inch-thick A110-AT titanium alloy and 0.028-inch-thick Type 430 stainless steel; the shear strength of these joints was about 940 pounds.[81] Additional work was undertaken by Weare and Monroe.[82] Joints were produced between 0.018-inch-thick A-70 titanium alloy and 0.020-inch-thick Type 316 stainless steel; the joint strengths were about 200 pounds.

Titanium alloys have been clad to various types of steel by explosive welding and brazing.

TABLE 7. TESTING OF DIFFUSION-WELDED Ti-8Al-1Mo-1V to 321 STAINLESS STEEL TUBULAR JOINTS[52]*

Specimen	Joint Diameter, inches	Thermal Shock 180 F to -320 F	Helium Leak	Vibration: Random 27 G's RMS[a]	Vibration: Sinusoidal 5 G's	Helium Leak	Cyclic Pressure, psig: 72 F 200 Cycles	Cyclic Pressure, psig: -320 F 200 Cycles	Helium Leak	Burst Test, psig: 72 F	Burst Test, psig: -320 F
C1	0.5	5 times	x				4400			11,600	
C2	0.5	Ditto	x				4400				
C3	0.5	"	x								
C4	0.5	"	x								
C5	0.5	"	x								
C6	2.0	"	x	15 min	10^5 cycles	x	1850			5,900	
C7	2.0	"	x	15 min	10^5 cycles	x	1850				
C8	2.0	"	x								
C9	2.0	"	x								
C10	2.0	"	x								
C11											
C12											
C13											
C14	4.0	"	x				1070			3,020	
C15	4.0	"	x				1070				
C16											
C17											
C18											
C19	8.0	"	x								
C20	8.0	"	x								
C21											
C22											
C23											

(a) Test duration 15 minutes

* x indicates test completed; blank space indicates test to be completed.

Titanium was diffusion welded to iron, Type 430 stainless steel, and Type 321 stainless steel using a vanadium foil as an intermediate metal.[78] These joints were extremely brittle because of the formation of a vanadium carbide intermetallic compound.

Titanium to stainless steel joints were cold welded by Kharchenko, et al.[79] After welding, the joints were annealed for periods up to 10 minutes at 1470 F in a vacuum. Then, mech-

According to the review prepared by Linse, Wittman, and Carlson, titanium and its alloys have been explosively welded to numerous carbon, low-alloy, and stainless steels by the patented DETACLAD process.[25] Another patented process, HORTONCLAD, has been developed to vacuum braze titanium to ferrous metals. An extensive program utilizing these procedures was used to clad titanium to mild steel using various silver-base brazing filler metals.[83] The strongest joints with shear strengths greater

than 20 ksi were produced by vacuum brazing with the silver-copper eutectic.

Titanium alloy Ti-8Al-1Mo-1V was roll welded to Type 321 stainless under the following conditions: (1) rolling temperature - 1050 F, (2) atmosphere-argon, and (3) diffusion aid - aluminum foil. [50] The stress to cause failure in the resulting joints ranged from about 7 to 8.7 ksi at room temperature, 5.6 to 6.3 ksi at 400 F, and 7.2 to 10.4 ksi at -423 F. [50]

Beryllium to Steel

Fusion Joining

Beryllium has been fusion welded to itself by means of the gas tungsten-arc and electron-beam welding processes. However, little or no no success has been achieved in fusion welding beryllium to ferrous alloys because of the formation of brittle intermetallic compounds. MacPherson indicated that a braze welding technique has been used to join beryllium to stainless steel using pure silver as the filler wire; however, the details on joining were not discussed. [84]

Nonfusion Joining

The most commonly used process to join beryllium to steel is brazing. In 1960, Glorioso, O'Keefe, and Rogers discussed the results of a limited investigation to braze beryllium to 17-7 PH stainless steel for a sandwich structure application. [85] The wetting and flow properties of several silver-base filler metals were evaluated by brazing tee specimens in a partial pressure of argon; the Ag-7Cu-0.2Li alloy produced joints with acceptable visual appearance. To further evaluate the behavior of this alloy, lap-shear specimens and a small sandwich panel were brazed. The lap-shear specimens had strengths ranging from 8 to 14 ksi. The sandwich panel consisted of 0.020-inch-thick face sheets of beryllium brazed to a core of 17-7 PH. Metallographic examination of the joints showed that excessive reaction between the filler metal and base metals had occurred.

An extensive program to fabricate honeycomb flat and curved panels for service at high temperatures was conducted by Krusos, et al. [86] QMV beryllium face sheets, 0.020 inch thick, were brazed to honeycomb core fabricated from such alloys as Type 321 stainless steel, 17-7 PH and 15-7PH precipitation-hardening stainless steels, and A286 heat-resistant alloy. Some panels consisted of a face sheet brazed to each side of the core material. More complex panels consisted of two layers of honeycomb core separated by a sheet of beryllium; face sheets attached to the outer surfaces of the core completed the assembly. During the initial phases of the program, experimental honeycomb panels were brazed to evaluate (1) the selected brazing filler metals, (2) the brazing cycle, and (3) the heating equipment. Quartz-lamp brazing, electric blanket brazing, and furnace brazing were evaluated; the panels were enclosed in an envelope so that brazing would occur in a partial pressure of argon. The filler metals used for joining were (1) Ag-7Cu-0.2Li, (2) Ag-28Cu, and (3) silver foil clad with Ag-7Cu-0.2Li; optimum joining occurred with the Ag-7Cu-0.2Li alloy. Quartz-lamp and electric blanket brazing equipment was well-suited to the production of flat or slightly curved panels; panels with more severely contoured surfaces were brazed in a furnace. This program demonstrated the feasibility of fabricating honeycomb panels with beryllium face sheets for aerospace applications. Panels were evaluated metallurgically and mechanically; the usual tests specified for sandwich structure (flatwise compression, tensile shear, etc.) were conducted.

A Type 303 stainless steel pressure fitting was joined to a 0.080-inch-thick sheet of QMV beryllium using pure silver as the filler metal. [87] The joint was eutectic diffusion brazed at 1690 F for 20 to 30 minutes in a vacuum; a pressure of 5 psi was applied to hold the joint members together. The quality of the brazed joint was evaluated by torque testing at 70 inch-pounds. During the course of this program, it was noted that the time the joint was exposed to a temperature in excess of the silver-beryllium eutectic temperature had to be minimized to prevent the formation of brittle intermetallics. Westlund has also conducted research on the vacuum brazing of beryllium to stainless steel. [88]

Research was conducted to fabricate cast beryllium-stainless steel tubular composites to serve as impact targets for the evaluation of beryllium's resistance to simulated meteoroid collisions. [89] Cast beryllium cylinders were machined to fit around a stainless steel tube with a clearance of 0.001 inch. Following plating of the stainless steel and beryllium joint members with silver, the parts were assembled and sealed in a retort. The retort was repeatedly evacuated and purged with helium; brazing was conducted in an argon atmosphere at 1625 F for 10 minutes. This appears to be an instance of eutectic diffusion brazing as was the work discussed in the preceeding paragraph. The joints were reasonably sound; some unbonded areas were revealed by radiographic and destructive tests.

QMV beryllium was brazed to Type 304L stainless steel to demonstrate the feasibility of joining these metals for nuclear applications. [90] The stainless steel component was chemically cleaned and placed in a vacuum chamber; further cleaning to remove chromium oxide was accomplished by electron bombardment of the steel surface. Then, the surface was coated with a thin film of the Ag-28Cu filler metal by vapor-deposition techniques. The beryllium and stainless parts

were assembled and brazed in a vacuum; brazing was conducted at 1510 F. The importance of closely fitting parts was emphasized. Lap-shear specimens were also prepared to determine the joint strength; shear strengths ranged from 14.2 to 20.5 ksi.

The use of the eutectic diffusion brazing process to join beryllium to stainless steel has already been cited. Research has been conducted to diffusion weld these metals also. In the course of developing procedures to fabricate the beryllium-stainless steel impact targets, cast beryllium-to-Type 316 stainless steel joints were made by diffusion welding.[89] Joining was done in a vacuum at 1450 F for 2 hours; silver was used as a diffusion aid. A 1/2-inch-diameter stainless steel tube was positioned inside of a drilled section of beryllium rod, 1-1/4 inches in diameter. Pressure was supplied by differential thermal expansion.

During a program to develop filler metals and procedures for joining refractory metals, Young and Jones studied the diffusion welding of beryllium to Type 316 stainless steel.[91] Disks of beryllium and stainless steel, 1/2 inch in diameter by 1/16 inch high, were machined, cleaned, assembled, and placed in a capsule; pressure was applied by means of a plug threaded in into the capsule. The first group of specimens was diffusion welded in a vacuum (10^{-5} torr) at temperatures of 1800 and 2000 F for 4 hours; no diffusion aid or barrier was used. Metallographic examination of these joints indicated the presence of a wide diffusion zone at the interface. Additional specimens were welded using copper as a diffusion barrier metal between the joint members; welding was done at 1500 F to minimize diffusion. Metallographic examinations and hardness measurements indicated that copper was ineffective as a diffusion barrier.

Gas pressure bonding, a variation of diffusion welding, was used to fabricate beryllium-clad tubular impact targets.[92,93] The impact targets were 6 inches in length and 1.220 inches in diameter. A beryllium sleeve was welded to a 0.500-inch-diameter Type 316 stainless steel tubing. Two types of beryllium were used during this investigation. QMV beryllium powder was cold hydrostatically pressed and machined to size. The other type was hot pressed, extruded, and annealed PX20-grade beryllium. The beryllium and stainless steel parts were assembled and gas-pressure bonded at 1400 F for 2 hours at a pressure of 10,000 psi. Successfully bonded impact targets were fabricated by these procedures. In a later program, a similar assembly was bonded using beryllium that was reinforced with stainless steel wire.

Ultrasonic welding procedures have been used to join a beryllium disk to a Type 321 stainless steel ring for use with low-energy-radiation detectors.[94]

Refractory Metals to Steel

Fusion Joining

Most of the research on joining the refractory metals to dissimilar metals has been concentrated on nonfusion joining methods. Several of these metals are susceptible to embrittlement from exposure to a contaminating atmosphere during joining. In addition, the mechanical properties of some of these base metals are reduced as the result of recrystallization during welding. To an extent, problems arising from contamination can be minimized by welding in a vacuum.

During investigations to extend the usefulness of electron-beam welding for production applications, welds were made in several columbium- and tantalum-base structural alloys. In the course of this work, a spun tantalum cap was electron-beam welded to a heavy-walled Type 321 stainless steel sleeve; the wall thickness of the tantalum cap was 0.060 inch.[95] During welding, the beam was focused mainly on the stainless steel section to permit the steel to become molten and wet the tantalum.

The use of the gas tungsten-arc and electron-beam welding processes to join molybdenum and columbium alloys to stainless steel was investigated by D'Yachenko, et al.[96] Flat butt and lap joints were electron-beam welded; the amount of heat applied to the high-melting metal was regulated by moving the molten pool away from the joint or by reducing the beam current. Under the proper conditions, the molten stainless steel wet the refractory metal well and produced a well-contoured joint. The average yield strength for molybdenum-stainless steel welds was 55.3 ksi for butt welds and 59.5 ksi for lap welds; welds using a modified butt-joint design with a raised edge on the stainless steel had an average yield strength of 82.3 ksi. For the columbium-stainless steel joints, the average yield strength was 71 ksi for lap joints. Welds were also made by the argon-shielded gas tungsten-arc process in a controlled atmosphere. The average yield strength for the molybdenum-stainless steel joints was 38.3 ksi for butt welds, 55.3 ksi for lap welds, and 71.4 ksi for the modified butt welds; the yield strength for lap welds between columbium and stainless steel was 64 ksi. The difference in yield strengths between welds made in a vacuum (electron beam) and those made in a controlled atmosphere (gas tungsten-arc) is directly related to the presence of gaseous contaminants in the controlled atmosphere. The effect of such contaminants on the mechanical properties of columbium welds was less pronounced than on those of molybdenum welds.

The welding of molybdenum-to-stainless steel joints by electron-beam procedures was also reported by Gatsek.[97] Tungsten was also joined

to stainless steel by gas tungsten-arc welding; an aluminum filler metal was used in joining.

Unpublished work conducted at Battelle involved the joining of molybdenum and columbium to stainless steel. The joints were used in corrosion-test loops to attach tubing connections to the refractory-metal loops. The molybdenum-stainless steel joints were made by a weld-brazing technique using pure nickel as filler metal. Similar techniques were used in the columbium-stainless steel joints except that Hastelloy W filler wire was used. All weld brazing was conducted in an inert-gas chamber using a tungsten-arc torch.

Research of a different nature was conducted by Stoner.[98] Techniques were developed to join bimetallic tubing used in applications involving high-temperature liquid metal containment. Coextruded bimetallic tubing has been produced to serve as mercury boiler tubes, an application in which the interior of the tubing is exposed to boiling mercury and the exterior is exposed to NaK at 1350 F. Effective joining techniques were needed to produce the usual plumbing-type joints. Tubing with an outside diameter of 0.800 or 0.510 inch was evaluated. The overall wall thickness of the tubing was 0.055 inch; the inner layer was unalloyed columbium, 0.020 inch thick, and the outer layer was Type 316 stainless steel, 0.035 inch thick. Electron-beam welding and gas tungsten-arc welding in a highly controlled atmosphere was used for joining butt joints, tee joints, and tube-to-header joints. The procedures used to make butt and tee joints are shown in Figures 9 and 10. As can be seen, the stainless steel cladding is removed from the joint area before the columbium weld is made; in this manner, the formation of brittle intermetallic compounds is prevented.

Nonfusion Joining

The nonfusion joining processes, such as brazing and diffusion welding, are well suited for joining the refractory metals to ferrous metals. Joining can be conducted in a vacuum or in a controlled atmosphere, thus preventing embrittlement from gaseous contaminants. Also, since fusion does not occur, the formation of undesirable intermetallics is minimized.

The brazing of a Cb-1Zr to Type 304L stainless steel transition section was discussed briefly by Bertossa.[5] Brazing was done in a vacuum; however, data on the filler and the brazing procedures were not given. It was noted that the time-temperature relationship during brazing was not as critical for this joint combination as it was for the titanium-stainless steel joint, because of the low reactivity of columbium.

The diffusion welding of molybdenum and columbium alloys to stainless steel was investigated by Young and Jones.[91] Small disks of

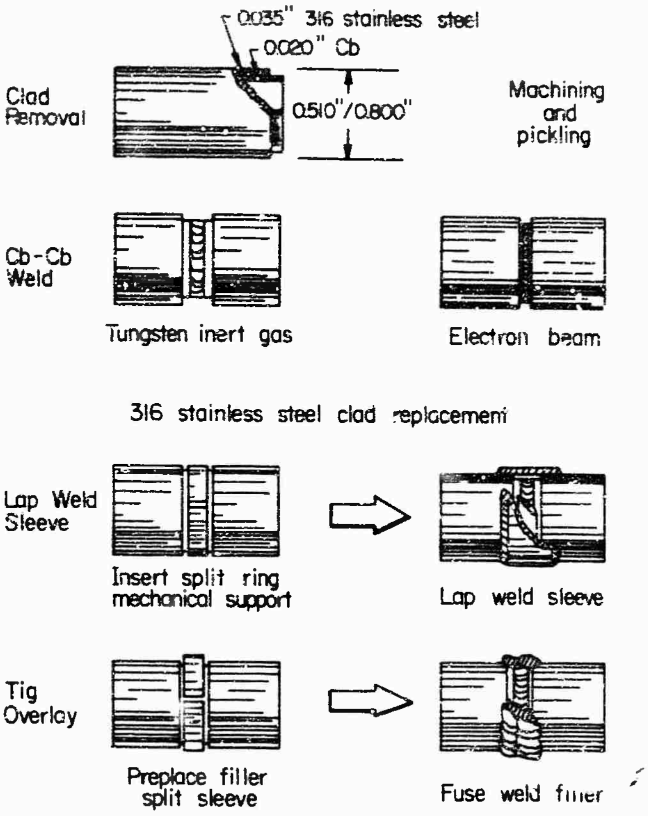


FIGURE 9. BUTT JOINT FABRICATION IN SEQUENCE[98]

columbium alloy F-48, molybdenum alloy Mo-0.5Ti, and Type 316 stainless steel were machined. The disks were assembled in a molybdenum capsule for joining; pressure was applied by means of a threaded screw in the capsule. Joints made between F-48 and 316 and between Mo-0.5Ti and 316 were diffusion welded at temperatures of 1800 and 2000 F for 4 hours. Joining was achieved in both cases, but microstructure examinations and hardness measurements indicated that brittle intermetallics formed. Tensile specimens (Cb-1Zr to 316) were diffusion bonded and tested. The maximum shear strength was 10.7 ksi at room temperature, 11.4 ksi at 600 F, 11.9 ksi at 1200 F, and 4.2 ksi at 1800 F.

Other methods that have been used to join the refractory metals to stainless steel include gas-pressure bonding, explosive welding, and ultrasonic welding.[39, 25, 82]

Nickel to Steel

The fabrication of joints between the nickel-base alloys and steels of various grades has always been an important area of joining technology; however, the joining of these metals has assumed new importance by virtue of their widespread use in aerospace and nuclear applications. Such joints combine the high-temperature strength, oxidation

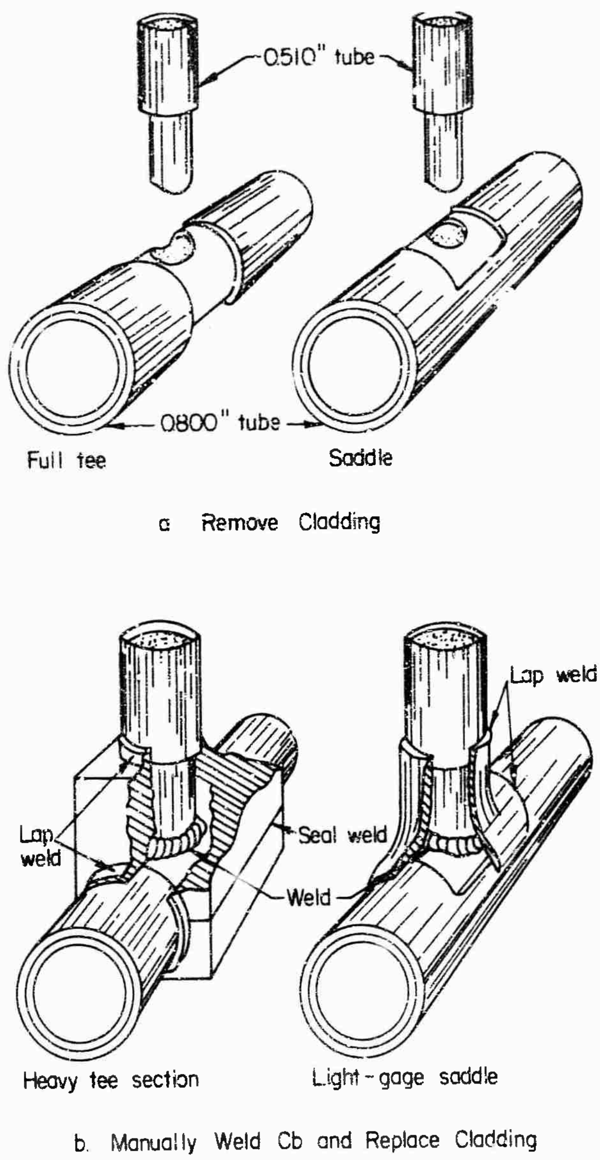


FIGURE 10. TEE-JOINT FABRICATION SEQUENCE (98)

resistance, and corrosion resistance of the conventional nickel-base alloys and the superalloys with the properties of a less expensive structural metal.

There is little justification for a detailed review of the accomplishments in joining these metals. The technology of joining is highly developed and it is well documented in the technical literature.(21, 99, 100) However, a few general comments are in order.

Fusion Joining

The arc welding processes are used most frequently to join the nickel-base alloys to ferrous metals. In many respects, the arc welding of these metals is very similar to the arc welding of stainless steels to less highly alloyed steels, and many of the same precautions in the selection of filler metals, welding processes, etc., must be observed. The difficulties experienced in joining these dissimilar metals are related mainly to the differences in composition of the respective base metals. The selection of the filler metal is based on such factors as (1) the effect of dilution at both base-metal interfaces, (2) the differences in the coefficients of expansion of base metals, and (3) the possibility of changes in the microstructure after long-time operation at elevated temperatures. The effect of dilution is of particular importance because of the agitation and mixing that occurs during fusion. The extent of dilution is highly dependent on the characteristics of the welding process, the speed of welding, the thickness of the base metal, the joint design, etc. The filler metal must be able to withstand dilution from both base metals without cracking, fissuring, or otherwise being subject to weld defects. The use of processes and welding techniques that produce minimum dilution should be considered in joining the nickel-base to ferrous metals. A few examples of joining are discussed briefly below:

(1) Inconel was joined to Type 304 stainless steel and carbon steel by the following means: shielded metal-arc welding, gas tungsten-arc welding, and gas metal-arc welding.(101) Welds meeting the stringent requirements for nuclear-plant service were obtained with all processes. Welds of a similar nature were made between heavy Inconel plate and carbon steel using specific nickel-base filler metals for shielded metal-arc and gas metal-arc welding.(102) Crack-free and porosity-free welds were obtained using various welding positions, restraints, and heat treatments.

(2) Research was conducted to determine the suitability of welds between nickel-base alloys and stainless steels for nuclear service at temperatures ranging from 650 to 2050 F.(103) The gas tungsten-arc process was used to weld: Hastelloy X to AISI 316 and AISI 347, and Hastelloy C to AISI 316 and AISI 347. Hastelloy W was used as the filler wire for all welds. All of the welds and heat-affected zones were sound, as determined by radiography, dye-penetrant testing, and macro- and micro-examinations. Most welds exhibited full joint efficiency at room temperature. The joint efficiency at 1800 F was highest for welds involving Hastelloy X.

(3) Further research was conducted to determine the effects of aging at elevated temperatures on the properties of welds between Hastelloy X-280 and AISI 316.(104) Joints between these metals were made by gas tungsten-arc welding with Hastelloy X or W filler wire; both

compositions are recommended for welding dissimilar nickel-base alloys. After joining, the welds were aged for 500, 1000, 5000 hours at temperatures of 1000, 1200, 1400, and 1600 F. On the basis of comparisons of weld-metal ductilities at room temperature and elevated temperatures, it was concluded that welds made with Hastelloy W filler metal most nearly met the joint requirements. Although both weld metals were embrittled by the aging treatment, aging was more sluggish in joints welded with Hastelloy W than with Hastelloy X.

These examples indicate the scope of research in developing procedures to weld the solid-solution strengthened nickel-base alloys to ferrous metals. The welding of the age-hardenable nickel-base alloys to dissimilar metals is not nearly so well covered in the literature. However, Hastelloy W has been used to weld such joints.

Research to develop filler-metal compositions for welding high-nickel alloys to austenitic stainless steels was conducted by Martyshin and Khorosheva. [105] To reduce the susceptibility of the weld metal to hot cracking, it was recommended that these base metals be joined with a nickel-chromium-molybdenum filler wire; data indicated an improvement in hot-cracking resistance without impairment of the mechanical properties of the joint.

Dissimilar metal joints between nickel-base alloys and ferrous metals have also been made by resistance spot welding. The welding procedures for spot welding age-hardenable Inconel 718 to AISI 301 are discussed in a recent publication by Girton. [106] The shear and tensile strengths of experimental spot welds were adequate at test temperatures of 75, -320, and -423 F.

Nonfusion Joining

Nonfusion joining processes, such as brazing, diffusion, welding, explosive welding, and friction welding, can be used to join the nickel-base alloys to ferrous metals when it is necessary to avoid problems of dilution; however, the most commonly used joining method is brazing. The problems involved in brazing these base metals are similar to those encountered in brazing dissimilar ferrous metals.

The selection of the filler metal, brazing process, and joining procedures is largely governed by the compositions and properties of the nickel-base alloy and ferrous metal and the expected service conditions. For low-temperature service, these metals can be joined with the silver- or copper-base alloys. Joints subjected to high-temperature conditions can be brazed with nickel-base filler metals, which possess excellent high-temperature strength and oxidation resistance. Also, a number of filler metals based on such noble metals as gold and palladium are available. Joints exposed to corrosive environments must be brazed with a filler metal that has the required resistance to corrosion. The melting characteristics of the brazing filler metal must also be compatible with the heat treatment required to develop optimum base-metal properties.

The nickel-base alloys should be in a stress-free condition during brazing, since they are subject to stress-corrosion cracking in the presence of molten filler metals. [22]

The brazing environment is highly dependent on the composition of the nickel-base alloys and the ferrous metals. The age-hardenable alloys contain significant amounts of titanium and/or aluminum. Since the oxides of these metals are not reduced at practical brazing temperatures, joints involving these metals must be brazed in a vacuum to insure adequate wetting by the filler metal. Other nickel-base alloys can be brazed in a reducing atmosphere.

The technology of brazing nickel-base alloys is well-documented the technical literature. [107 - 110] This technology is generally applicable to the brazing of dissimilar-metal joints involving nickel-base alloys and the stainless steels.

JOINING DISSIMILAR NONFERROUS METALS

The inherent problems in joining dissimilar nonferrous metals are similar to those encountered when ferrous and nonferrous metals are joined, because of the differences in the physical and metallurgical properties of the base metals. Some dissimilar nonferrous metals have been joined routinely for many years; others, such as aluminum to titanium, titanium to nickel, aluminum to uranium, etc., are new combinations that owe their existence to their application in aerospace and nuclear hardware. Recent developments in this area of joining are discussed in succeeding sections

Aluminum to Titanium

Fusion Joining

The joining of aluminum alloys to those of titanium has not been accomplished successfully by conventional arc welding processes. During fusion, these metals form intermetallic compounds that are exceedingly brittle. In 1963, Fridlyand, et al., conducted research on the joining of these metals, and a method of calculating the temperature/time relationship under which the intermetallic compound Al_3Ti would not form was developed. [111] During this investigation it was noted that the small amount of Al_3Ti that formed during the welding of titanium and pure aluminum (without fusing the titanium) had almost no effect on the mechanical

properties of the joint. Therefore, it was recommended that the titanium joint surfaces be overlaid with pure aluminum before welding. This technique of "buttering" is often used during the welding of dissimilar metals.

Moderate success has been reported in the resistance spot welding of aluminum to titanium in association with a program to evaluate this method as a technique to join titanium to other metals. (66)

Nonfusion Joining

Nonfusion joining procedures are more suitable for fabricating aluminum-to-titanium joints, because the formation of brittle intermetallic compounds is minimized by the absence of fusion. In 1965, Gatsek indicated that these metals had been soldered after plating the titanium and aluminum surfaces with nickel; however, few details of the joining operation were given. (112)

Bollenrath and Metzger conducted an extensive program to develop and evaluate filler metals and procedures for brazing commercially pure titanium to aluminum. (113) Joints whose tensile and shear strengths were greater than those of the aluminum base metal were obtained by dip brazing in a molten flux. The filler metal Ag-33Al was used to braze (1) the pure aluminum-to-titanium joints, and (2) the 6061 aluminum alloy-to-titanium joint; and Al-50Zn filler metal was also used to join commercially pure aluminum to titanium. Before brazing, the joint surfaces were coated with the filler metal; this was accomplished by hot dipping into a flux-covered metal bath. The best joints were made by dip-brazing procedure; torch brazing was possible, but air-furnace brazing was not. The tensile and shear strengths for brazed titanium-to-6061 aluminum alloy joints after hardening were 31.7 and 25.2 ksi, respectively. The atmospheric corrosion resistance of the Al-50Zn filler metal was better than that of the Ag-33Al alloy.

Investigations indicate that sponge aluminum can be joined to the titanium alloy Ti-3Al-1.5Mn. (114) To achieve satisfactory results, it was necessary to coat the titanium surfaces with commercially pure aluminum in a flux-covered bath maintained at a temperature of 1470-1560 F; the most ductile joints were obtained with a coating time of 30-40 seconds. Zinc-cadmium, zinc-aluminum, and zinc-aluminum-copper filler metals were used for brazing. Abrasive action during brazing was used in lieu of a flux. Good shear strength in the temperature range of 70 to 570 F and adequate resistance to seawater corrosion were reported. The titanium alloy was also brazed to sintered aluminum powder using the same procedures.

The diffusion welding of Type 2219 aluminum alloy to Ti-5Al-2.5Sn titanium alloy was investigated during a program to fabricate transition sections for cryogenic tubing applications. (50,52) The joints were diffusion welded in air or in a vacuum using bare or silver-plated base metals. Based on metallurgical studies, corrosion tests, and mechanical tests, the following conditions were selected for welding: (1) bare base metals: 940 F for 30 minutes in a vacuum and (2) silver-plated base metals: 500 F for 2 hours in air. Acceptable shear strengths at all test temperatures were obtained with bare base metals. Joints made with silver-plated base metals had acceptable strengths at room temperature and -320 F; low shear strengths were obtained at 300, 500, and -423 F, because of thermal stress resulting from the difference in thermal expansion of the joint members. Tubular transition sections were made using the tooling and joint design shown in Figures 6 and 7. In an extension to this program, joints between Type 2219 aluminum alloy and Ti-5Al-2.5Sn titanium alloy are being diffusion welded to produce transition sections of 0.5, 2.0, 4.0, and 8.0 inches in diameter. (52) The joint properties are being evaluated by thermal-shock tests, helium-leak tests, vibration tests, cyclic pressure tests, and burst tests; the results to date are shown in Table 8.

Aluminum-to-titanium joints have been produced by cold deformation welding and roll welding. Hughes and Shestakov discussed the cold welding of these metals; however, the details of joining were not presented. (80,55) Shestakov indicated that the amount of deformation was different for each metal, since aluminum and titanium vary so much in their plastic properties; the amount of deformation was controlled by the distance each metal projected from the cold welding dies. Crane, et al., investigated the roll welding of Type 2219 aluminum alloy to Ti-5Al-2.5Sn titanium alloy. (31) The lap shear specimens were abrasively cleaned and sealed in an envelope through which argon passed; rolling was conducted at 950 F with bare specimens. The shear-failure stress at various test temperatures for these specimens was (1) 23.1 ksi at room temperature, (2) 20.7 to 23.3 ksi at 300 F, and (3) 10.0 to 11.4 ksi at -423 F.

Joints between aluminum and titanium alloys have also been made by friction welding and explosive welding. (60,25)

Aluminum to Copper

Fusion Joining

The use of conventional fusion-welding processes to join aluminum to copper is limited by the formation of brittle intermetallic compounds

TABLE 8. TESTING OF DIFFUSION-WELDED 2219 ALUMINUM ALLOY TO Ti-5Al-2.5 Sn ALLOY TUBULAR JOINTS[52]*

Specimen	Joint Diameter, inches	Thermal Shock +180 F to -320 F	Helium Leak	Vibration: Random 27 G's RMS[a]	Vibration: Sinusoidal 5 G's	Helium Leak	Cyclic Pressure, psig: 72 F 200 Cycles	Cyclic Pressure, psig: -320 F 200 Cycles,	Helium Leak	Burst Test, psig: 72 F	Burst Test, psig: -320 F
B1	0.5	' times	x				4480				
B2	0.5	ditto	x				4480				
B3	0.5	"	x								
B4	0.5	"	x								
B5	0.5	"	x								
B6	2.0	"	x	11.3 min[b]		x					
B7	2.0	"	x	15 min	10^5 cycles	x	1920				
B8	2.0	"	x	15 min	10^5 cycles	x	1920				
B9	2.0	"	x								
B10	2.0	"	x								
B11											
B12											
B13											
B14	4.0	"	x				945				
B15	4.0	"	x				945				
B16											
B17											
B18											
B19	8.0	"	x								
B20	8.0	"	x								
B21											
B22											
B23											
B24											
B25											
B26											

(a) Test duration 15 minutes.
(b) Failed in root of specimen fitting.
* X indicates test completed; blank space indicates tests to be completed.

during the fusion process. In an early article, Cook and Stavish discussed the gas metal-arc welding of aluminum to copper; before welding, a layer of a silver-base filler metal (Ag-15.5Cu-17.5Zn-18Cd) was deposited on the surfaces of the copper workpiece.[115] A consumable aluminum-base filler wire was used for welding. Tin and aluminum have also been deposited on the copper surfaces before welding.

During a recent investigation, procedures were developed to join aluminum to copper by gas tungsten-arc welding; commercially pure aluminum was used as the filler wire.[116] The edges of the copper workpieces were bevelled in different ways to achieve the proper heat balance. During welding, the arc was directed toward the copper as filler wire was added. Despite these precautions, the joints did not possess the required strength or ductility. Fusion welds were also made by the submerged-arc process. The use of various coatings on the copper surfaces to reduce dilution of the weld metal was investigated. Optimum joint properties were obtained when the edge of the copper workpiece was bevelled at an angle of 75 degrees and coated with zinc.

The arc-spot method of welding has also been applied to the joining of aluminum to copper.[44] A shallow hole was drilled in the copper section and aluminum was deposited in it. A smaller diameter hole was drilled in the aluminum workpiece. The joint members were aligned so the holes coincided; then, an arc-spot weld was made using an aluminum filler metal.

Aluminum-to-copper busbar connections have been produced by flash welding for the electrical industry. Andreev, et al., investigated the use of this process to produce aluminum-copper transition sections that could be used for joining in the field.[117] Coatings of various silver-base alloys or brass were applied to the copper workpiece surfaces by means of an oxyacetylene torch. The welds were made by the continuous flashing process to break up and expel any intermetallic compounds that formed furing welding.

Nonfusion Joining

There are well-developed industrial processes to produce aluminum-to-copper joints by cold deformation welding. Portable and automatic equipment has been designed for making such joints, mostly for use in the electrical and wire-drawing industries. The cold-welding process is covered adequately in the technical literature and will not be discussed further.[118-120]

Aluminum-to-copper joints can be made by diffusion welding. In 1955 Storchheim conducted a laboratory study of the process parameters involved in producing joints with these metals.(121) It was found that acceptable joints were produced under the following conditions: (1) temperature - 880 F, (2) pressure - 40 ksi, and (3) time - 4 minutes. The welds were produced in a vacuum. Other joints were produced at a temperature of 1000 F and a pressure of 22 ksi for 4 minutes. Kazakov diffusion welded specimens from these metals at a temperature of 970 F and a pressure of 1.4 ksi for 10 minutes.(122)

The friction welding of aluminum-to-copper joints has been reported by Hazlett.(123) Joints between Type 2014 aluminum alloy and copper, 0.250 inch in diameter, were made at a rotational speed of 3200 rpm using welding and forging pressures of 5.6 ksi. Because of the formation of a brittle intermetallic, the joint strength was low; however, such joints could be used in electrical conductors because little strength is required.

Aluminum has also been explosively welded to copper base-plate material.(124, 25)

Short copper-aluminum transition sections are used in large numbers in the refrigeration industry for use in joining copper and aluminum tubing. These sections are usually produced by pressure welding.

Aluminum to Uranium and Zirconium

Joints between aluminum alloys and alloys of uranium and zirconium are encountered in the fabrication of fuel elements for nuclear reactors, and an extensive technology for joining these metals has been developed. Research has been concentrated on the following nonfusion joining methods: diffusion welding and roll welding for aluminum-to-uranium joints, and explosive welding and pressure welding for aluminum-to-zirconium joints.

The diffusion welding of aluminum to uranium has been discussed in detail by Schneider.(125, 126) A technique using zinc or tin as the intermediate metal or diffusion aid was developed to produce joints that were suitable for use in fabricating fuel elements for a low-temperature, water-cooled reactor; for higher coolant temperatures, nickel was used as the diffusion aid.(125) Further research was conducted to investigate the effects of the process variables on the properties of joints between aluminum (99.5Al) and an Al-4.5U alloy when nickel was used as a diffusion aid.(126) In particular, the growth of the nickel-aluminum and nickel-uranium intermetallic compounds at various welding temperatures and times was studied. Metallographic studies were conducted by Angerman to identify the microstructural constituents in joints welded with nickel as the diffusion aid.(127) Further research on the aluminum-nickel-uranium system was undertaken by Auleta.(128) Joints were diffusion welded at 750 F and 120 psi. The joints were held at this temperature for periods of 1000, 2000, and 4000 hours.

The eutectic-diffusion brazing process was also used to join aluminum to uranium.(129) The UO_2 fuel pellets were contained in a silver-plated aluminum-alloy tube. Joining studies were conducted in an inert atmosphere at a temperature of 1050 F and a pressure of 5 ksi. The silver-aluminum eutectic forms at this temperature to complete the joint; the eutectic-composition alloy diffuses into the base metals as a result of continued heating at this temperature.

Roll welding was investigated by Francis and Craig as a method to clad uranium-aluminum alloy and UO_2-aluminum dispersion cores with aluminum alloys.(130) Fuels with less than 20 weight percent uranium were readily clad with commercially pure aluminum. Alloy cores with a higher uranium content were clad with Type 6061 aluminum. Similar work was reported by Baskey.(131) A 40 volume percent uranium-bearing Fiberglass core was clad with Type 6061 aluminum alloy at a temperature of 1100 F; the composite thickness was reduced 50 to 65 percent during rolling. Roll-welded aluminum-clad fuel elements containing a uranium-aluminum alloy core were produced by Lloyd and Davies.(132) The uranium-aluminum fuel elements were heated to 580-600 C (1076 - 1112 F) and hot rolled, with a reduction in thickness of 60 percent; the rolling speed was 90 to 100 feet per minute.

The hot-press welding of Zircaloy-2 to aluminum and SAP (sintered aluminum powder) was investigated by Watson.(133, 134) Tubing joints were prepared by heating a tapered tube and pressing it into a thick-walled tube by hydraulic pressure. Commercially pure aluminum was welded to Zircaloy-2 without difficulty, even when a thin layer of oxide was present on the base metal surfaces; no deterioration in bend strength was noted after the joints were heated for 1000 hours at 500 F. Good bond strength was also obtained with joints between Zircaloy-2 and SAP. Joints made in this manner were used as transition sections.

Explosive welding has also been used to fabricate aluminum-to-zirconium alloy transition sections. Segel developed procedures to line Zircaloy-2 tubing with aluminum by means of explosive welding; for good joining, it was necessary to oxidize the joint surfaces and evacuate the space between the tube walls.(135) Strong but discontinuous joints were produced at pressures of 10^4 to 10^5 psi; at higher welding pressures the joints were continuous but the tubing dimensions could not be maintained. Porembka, et al., fabricated Zircaloy-4 to aluminum transition

sections with an outside diameter of about 3.5 inches.[136] Sound joints were produced when a 0.015 to 0.030-inch interface gap was employed and a central charge was detonated to expand the inner aluminum tube onto the zirconium-alloy tube.

Titanium to Nickel

Fusion Joining

Titanium is difficult to fusion weld to nickel-base alloy, because it forms brittle intermetallic compounds with almost every element contained in such alloys (Ni, Fe, Cr, Mn, and Si). Gorin conducted research to develop methods to fusion weld titanium alloy Ti-1.7Al-1.4Mn to a nickel-base superalloy whose nominal composition was Ni-22.4Cr-9.7Fe-3.1Al-1.1Ti-1.1Mn.[137] Manual and automatic gas tungsten-arc welds were made with bare workpieces and with nickel or molybdenum; such joints were not successful. Similar joints were made with considerable success using inserts of columbium and a high-copper alloy, Cu-2.0Be-0.35Ni. Titanium can be joined to columbium without forming harmful intermetallics; similarly, nickel-base alloys can be joined to the copper alloy. The average tensile strength of automatic arc-welded joints (0.08 inch thick) was 60 ksi at room temperature; the average bend angle was 48 degrees. The average tensile strength of similar joints made by manual gas tungsten-arc welding was 59 ksi at room temperature and 56 ksi at 750 F; the average bend angle was 70 degrees.

During the same program, procedures were developed to electron-beam weld the titanium alloy to the nickel-base alloy; the base-metal thicknesses ranged from 0.032 to 0.080 inch. Satisfactory joints were produced by (1) welding the titanium alloy to a columbium insert, (2) welding the nickel-base alloy to the copper-alloy insert, and (3) welding the inserts together.

Gorin also investigated the use of inserts to resistance spot and seam weld these two base metals. Excellent spot-welding results were obtained using insert foils of molybdenum, columbium, and tantalum. Optimum seam-welded joints were produced using a columbium foil insert or a plasma-arc sprayed coating of molybdenum between the joint surfaces. The problems associated with spot welding titanium to nickel were also investigated by McBee, Henson, and Benson.[66]

Nonfusion Joining

Several nonfusion joining processes have been investigated to determine their usefulness in joining titanium to nickel alloys. Joints between titanium alloy Ti-1.7Al-1.4Mn and nickel-base alloy Ni-22.4Cr-9.7Fe-3.1Al-1.1Ti-1.1Mn were brazed in an argon atmosphere at 1600 F for 5 minutes using the silver-copper eutectic alloy Ag-28Cu.[137] The average lap strength of these joints was 80 ksi at room temperature and 54 ksi at 750 F; the base-metal thickness was 0.040 inch.

The diffusion welding of titanium alloy Ti-8Al-1Mo-1V to nickel alloy Inconel 600 was also investigated during a program to fabricate transition sections for cryogenic tubing applications.[50] The joints were diffusion-welded in air or in a vacuum using bare, silver-plated, or nickel-plated base metals. The following conditions were used for welding: (1) bare base metals - 1625 F for 15 minutes in a vacuum, (2) silver-plated base metals - 600 F for 30 minutes in air, and (3) nickel-plated base metals - 1325 F for 30 minutes in a vacuum. Specimens welded in the bare condition produced acceptable shear strengths at all test temperatures. Either the silver- or nickel-plating functions as an effective diffusion aid resulting in lower permissible welding temperatures; however, the joint strength was not improve by plating.

During the same program, Ti-8Al-1Mo-1V was roll welded to Inconel 600 at a temperature of 1050 F; no diffusion aid was used.

In an article concerned with the fundamentals of friction welding, Hazlett discussed the appearance of the microstructure of a friction-welded titanium-to-nickel joint.[138] Some diffusion of nickel into titanium occurred, presumably due to the formation of the nickel-titanium eutectic during welding.

Review-type articles indicate that titanium and nickel alloys have been successfully joined by explosive welding.

Titanium to Beryllium

Beryllium has been most successfully joined to titanium by brazing procedures. In 1960, a program to develop beryllium sandwich structure was discussed by Glorioso, et al.[85] Following a series of wetting tests conducted to evaluate selected brazing filler metals, beryllium-to-titanium alloy RS140 lap-shear specimens were brazed with a proprietary filler metal (Ag-5Al-0.2Mn). The lap-shear strength of these joints varied from 8.1 to 16.0 ksi. Face sheets of 0.060-inch-thick beryllium were brazed to a core of commercially pure titanium; brazing was done in a partial pressure of argon.

A thorough study of the eutectic diffusion brazing of QMV beryllium to titanium alloy Ti-6Al-4V was undertaken by Cline and O'Neill to determine the most suitable filler metal for the intended application.[87] The properties of joints brazed with the following filler metals were evaluated: (1) pure silver, (2) Ag-15Mn, (3) Ag-0.2Li, (4) Ag-5Al-0.2Mn, and (5) Ag-7.3Cu-0.2Li. The results of the brazing studies are summarized in Table 9.

TABLE 9. SUMMARY OF STUDIES ON BRAZING QMV BERYLLIUM TO TITANIUM[87]

No.	Ti Alloy	Braze Material	Brazing Process	Brazing Atmosphere	Brazing Temp, F	Time at Temp, min	Joint Pressure, psi	Joint Area, sq in.	Test Temp, F	Ultimate Tensile Strength, psi	Location of Failure
1	Ti-6Al-4V	Ag	Induction	Purified argon	1700	10	40	0.2	1060	5,300	Be-Ag interface
2	Ti-6Al-4V	Ag with steel disk	Induction	Purified argon	1700	10	40	0.2	1060	7,250	Partially in Be
3	Ti-6Al-4V	Ag	Induction	Purified argon	1560	60	40	0.2	1060	5,000	Be-Ag interface
4	Ti-6Al-4V	Ag-15Mn	Induction	Purified argon	1795	10	40	0.2	1060	2,500	Be-Braze interface
5	Ti-6Al-4V	Ag-5Al-0.2Mn	Induction	Purified argon	1545	10	40	0.2	1060	11,700	Partially in Be
6	Ti-6Al-4V	Ag-5Al-0.2Mn with flux	Induction	Purified argon	1545	10	40	0.2	1060	10,300	Partially in Be
7	Ti-6Al-4V	Ag-7.3Cu-0.2Li	Induction	Purified argon	1645	10	40	0.2	1060	15,200	Partially in Be
8	Ti-6Al-4V	Ag-7.3Cu-0.2Li	Induction	Purified argon	1645	10	40	0.2	1060	13,000	Partially in Be
9	Ti-6Al-4V	Ag	Vacuum (a)	2.5×10^{-5} (b)	1660	7.5(c)	5	3.0	1060	2,330	Be-Ag interface
10	Ti-6Al-4V	Ag	Vacuum (a)	2.5×10^{-5} (b)	1680	7(c)	5	3.0	1060	1,700	Be-Ag interface
11	Ti-6Al-4V	Ag	Vacuum (a)	2.5×10^{-5} (b)	1680	6.4(c)	5	3.0	RT	11,000	Be-Ag interface
12	Ti-6Al-4V	Ag-7.3Cu-0.2Li	Vacuum (a)	2.5×10^{-5} (b)	1645	8(c)	5	3.0	1060	4,200	Partially in Be
13	Ti	Ag	Resistance	Argon	1800	(d)	80	0.07	RT	29,000	Be-Ag interface
14	Ti	Ag	Resistance	Argon	1800	(d)	80	0.4	RT	17,000	Partially in Be
15	Ti	Ag with V disk	Induction	Vacuum 1.5×10^{-2} mm	1780 on Ti side	(e)	40	0.2	RT	46,800	Beryllium
16	Ti	Ag with V disk	Induction	Vacuum 1.5×10^{-2} mm	1780 on Ti side	(e)	40	0.2	1060	15,100	Be-Ag interface
17	Ti	Ag-0.2Li with V disk	Induction	Vacuum 1.5×10^{-2} mm	1780 on Ti side	(e)	40	0.2	RT	37,400	Partially in Be
18	Ti	Ag-0.2Li with V disk	Induction	Vacuum 1.5×10^{-2} mm	1780 on Ti side	(e)	40	0.2	1060	11,200	Ag-V interface

(a) Identifies furnace.
(b) mm of Hg.
(c) Time above 1600 F.
(d) Time above 1600 F was 20 sec.
(e) Time above 1600 F was 3 to 10 sec.

For elevated temperature service, the most satisfactory results were obtained by outgassing the beryllium before joining. During brazing, the time above the beryllium-silver eutectic temperature, about 1620 F, was critical. Some studies with barrier metals to minimize diffusion were also conducted, and these results also appear in Table 9; steel and vanadium were evaluated as barrier metals.

Westlund also investigated the eutectic diffusion brazing of beryllium-to-titanium joints using silver-base filler metals.[88] While in agreement with the temperature limits discussed above, some joints between beryllium and B120 VCA titanium alloy were brazed with pure silver in a vacuum at 1650 F; these joints had shear strengths of about 20 ksi. These joints resulted from the formation of the beryllium-silver eutectic.

Diffusion welding was also investigated by Cline and O'Neill as a method to join these metals.[87] QMV beryllium was joined to Ti-6Al-4V titanium alloy at a temperature of 1570 F and a pressure of 640 psi in a vacuum. A silver foil, 0.003 inch thick, was used as a diffusion aid. The strength of these joints was about 5 ksi.

Titanium to Copper

The physical properties of titanium (melting point, expansion coefficient, thermal conductivity, crystal lattice, etc.) differ widely from those of copper; in addition, the solubility of copper in α-titanium is low. Thus, the joining of these metals presents many difficulties. Nevertheless considerable research has been undertaken to join titanium to copper by fusion and nonfusion procedures.

Fusion Joining

In research conducted by Mikhailov, et al., it was noted that the solubility of copper in β-titanium is about 17.7 percent at 1820 F as opposed to a solubility of 2.1 percent in α-titanium at the eutectoid temperature.[139] A series of experimental alloys containing β-stabilizers was produced for this investigation. Included were Ti-20Mo, Ti-20Cb, Ti-30Cb, and Ti-30 Ta; the titanium alloys were rolled to a thickness of 0.060 to 0.080 inch. Joints between those alloys and commercially pure copper were made by gas tungsten-arc welding. Joints between a β-titanium alloy Ti-3Al-6.5Mo-11Cr and copper were also made. The joints with the highest tensile strength and ductility were those produced with Ti-30Cb and Ti-3Al-6.5Mo-11Cr. Similar results were obtained with joints between the titanium alloys and copper-base alloy Cu-0.8Cr. The joints between Ti-30Cb and Cu-0.8Cr had an average tensile strength of 39 ksi and a bend angle of 137 degrees; the average tensile strength and bend angle of the Ti-3Al-6.5Mo-11Cr to Cu-0.8Cr joints were 29.5 ksi and 162 degrees, respectively.

Additional research on the fusion joining of titanium to copper was conducted by Strizhevskaya and Starova during the course of a program on joining dissimilar metals.[140] Titanium alloy Ti-3Al-1.5Mn was electron-beam welded to Cu-0.8Cr copper alloy. With preferential melting of the copper, the joints had relatively low strength (7.1 to 14.2 ksi) and low ductility. There was a diffusion layer at the titanium interface that was very hard and brittle. Gas tungsten-arc welds were made between these base metals using columbium as an intermediate metal; these joints were quite ductile, having a bend angle in excess of 100 degrees.

Nonfusion Joining

Titanium alloy Ti-3Al-1.5Mn has been brazed to Cu-0.8Cr alloy using silver-base filler metals.[141] Three filler metals were evaluated during this program: (1) Ag-28Cu, (2) Ag-40Cu-35Zn, and (3) Ag-27Cu-5Sn. The joints were brazed in a vacuum at a temperature of 1520 F for 5 minutes. Using these conditions, shear strengths of 28.4 to 38.3 ksi were obtained. The heating rate and brazing temperature were critical. Heating rates lower than 85 F per minute produced joints with lower shear strengths. For maximum joint strength, the brazing temperature had to be between 1518 and 1526 F.

A process for vacuum brazing copper-plated titanium was also developed.[142] Copper was electroplated on the surface of titanium alloy Ti-3Al-1.5Mn after the surface had been hydrided in a sulfuric acid solution. Joints were made between the titanium alloy and commercially pure copper (as well as between Ti-3Al-1.5Mn and stainless steel or a nickel-base alloy) using Ag-27Cu-5Sn filler metal. The joints were brazed under pressure at 1400 to 1500 F for 15 to 20 minutes. Increased times and temperatures increased the diffusion-zone thickness and lowered the joint strength. Under ideal conditions, the average shear strength was about 28 ksi.

The diffusion welding of titanium alloys to high-copper alloys was investigated by Shmakov and Izmirlieva.[143] Joints were made between Ti-3Al-1.5Mn, Ti-4Al-3Mo-1V, and Ti-3Al-8Mo-11Cr alloys and Cu-0.8Cr alloy. The optimum joining conditions were (1) temperature - 1750 to 1796 F, (2) pressure - 280 to 500 psi, and (3) time - 5 hours. A columbium foil, 0.004 inch thick, was used as a diffusion aid. The tensile strength of these joints ranged from about 27.5 to 40.7 ksi.

Joints between titanium and copper have been cold welded also.[144] Specially shaped workpieces were assembled in a die set and joined

at a pressure of 6000 pounds. After welding, the joints were heat treated at 400 to 1470 F for 1 hour. A gradual decrease in joint strength occurred with increasing heat-treatment temperature.

Titanium to Columbium

Several columbium alloys were fusion welded to unalloyed titanium during the course of a program to develop techniques for joining refractory metals.[145] The inert-gas tungsten-arc welding process was used to join 0.012-inch-thick titanium foil to 0.018-inch-thick columbium alloy D43. Other joints between titanium and columbium alloys D43, B66, and Cb752 were made by electron-beam welding. Well-bonded joints were obtained in all of these metal combinations. Minor problems were encountered because of the difference in the melting points of titanium and columbium and because the foils were not of the same thickness. These problems were overcome by changes in the welding techniques.

Columbium was welded to several titanium alloys during a program to study the metallurgical aspects of joining α- and β- titanium alloys to dissimilar metals.[140] Columbium is metallurgically compatible with titanium and is frequently used as an intermediate metal to facilitate joining other metals to titanium. Gas tungsten-arc and electron-beam welds were made between columbium and the following titanium alloys: Ti-3Al-1.5Mn, Ti-4Al-3Mo-1V, and Ti-3Al-8Mo-11Cr. The tensile strengths of these joints were as follows: (1) Cb to Ti-3Al-1.5Mn - 73.2 ksi at 68 F and 62.4 ksi at 570 F, (2) Cb to Ti-4Al-3Mo-1V - 76 ksi at 68 F and 63.2 ksi at 570 F, and (3) Cb to Ti-3Al-8Mo-11Cr - 75.2 ksi at 68 F and 61.2 ksi at 570 F. All of the joints exhibited excellent ductility.

During this program, zirconium was also arc welded to Ti-3Al-1.5Mn. The tensile strength of these joints was 61.7 ksi at 68 F and 34.0 ksi at 570 F.

Refractory-Metals Joining

Extensive research on joining columbium, molybdenum, tantalum, and tungsten and their alloys to themselves and to other metals has been conducted in recent years, because of the demands of the aerospace and nuclear industries for high-temperature materials. Most of the research has been concentrated on nonfusion joining methods, since joining can usually be conducted under conditions that do not adversely affect the mechanical properties of the base metal or joint. The characteristics of the refractory metals must be considered carefully in selecting the joining procedures. In particular the effects of recrystallization on the mechanical properties of such metals as molybdenum and tungsten must be considered. Most of the refractory metals are embrittled by gaseous contaminants, so the environment associated with the joining method must be considered.

Developments in fusion and nonfusion joining of dissimilar refractory metals are discussed in the sections below. Also included are developments in joining the refractory metals to other heat-resistant materials.

Fusion Joining

Reports on research to join dissimilar refractory metals by fusion-welding methods are scarce. In a recent paper, Gatsek indicated that the following metals had been joined by electron-beam welding: (1) tungsten to molybdenum, (2) molybdenum to columbium, and (3) molybdenum to stainless steel.[112] However, details on the joining procedures and joint properties were not presented.

During a program to develop techniques for joining refractory-metal foils, the following joints were made by gas tungsten-arc welding in a controlled-atmosphere chamber: (1) Cb752 columbium alloy to T111 tantalum alloy and (2) D43 columbium alloy to T111 tantalum alloy.[145] The base-metal thickness was 0.012 inch in all cases. Metallographic examinations indicated that all joints were sound and that there was very little intermixing of the alloy constituents at the fusion line. The mechanical properties of the D42-T111 joints at room temperature and at elevated temperature are shown in Table 10.

Nonfusion Joining

During an early program to develop bimetallic materials for possible missile applications, vacuum brazing was used to join tantalum sheet to OFHC copper plate.[146] This joint combined the high-temperature strength and abrasion resistance of tantalum and the heat-dissipation capabilities of copper. The bimetallic material was produced in plate form; then, the plate was cold drawn into a nose-cone configuration for evaluation in rapidly flowing oxidizing gases at 3600 F. Joints that withstood this environment for a 1-minute performance period were produced with the following brazing filler metals: (1) u-8Sn, (2) Au-18Ni, and (3) Ag-15Mn.

Brazing was investigated as a method to join the components of a propulsion engine for service at elevated temperatures.[147] Such an engine operates with hydrogen as the thrust gas, and the joints must remain gas-tight for several hundred hours. During operation, the joint temperatures vary from 1650 to 2200 F or higher. After an investigation of the prope ies of several commercial and experimental filler metals, the following filler metals were selected to join the tungsten nozzle to the molybdenum plenum: (1) pure iron for service at temperatures up to 1800 F and (2)

TABLE 10. TENSILE PROPERTIES OBTAINED IN TIG WELDS OF 0.012-INCH T111 FOIL TO D43 FOIL COMBINATIONS[145]

Temperature, F	Tensile Strength, psi	Yield Strength, psi	Elongation in 1.0 Inch, percent	Location of Failure[a]
1500	58,500	45,400	6.0	Parent material
1500	58,500	46,600	3.5	Edge of weld
2000	47,700	38,300	7.0	Parent material
2000	46,500	36,900	10.0	Parent material
2250	37,600	34,700	10.0	Edge of weld
2250	37,200	31,200	13.5	Parent material
2500	24,600	23,900	20.5	Parent material
2500	28,800	26,900	21.0	Parent material
Room	80,200	60,800	1.0	Parent material
Room	61,400	59,200	1.0	Edge of weld

(a) All failures in parent metal occurred on the D43 side of the welded joint.

Cr-25V alloy for service up to 2700 F. The joints were brazed in a controlled-atmosphere of hydrogen or argon.

The results of a program to develop procedures to fabricate lightweight sandwich structures for service at temperatures up to 2000 F were reported by Titus, Nickell, and Burns.[148] Filler metals were evaluated for use in brazing TZM molybdenum face sheets to Inconel 702 honeycomb core. For this application, the filler metal had to wet both base metals well without causing erosion of the thin foil used in the face sheets or honeycomb core. Also, the melting range of the filler metal was restricted to 2200 F and below to avoid recrystallization of the molybdenum alloy. The performance of filler metals in the gold-palladium and silver-palladium alloy systems was investigated; silver-palladium alloys produced joints with the least erosion of the base metals.

Research to join representative refractory metals to high-strength, heat-resistant superalloys was also undertaken by Welty, et al., during a program to join refractory-metal foils.[145] Joints were vacuum brazed between Hastelloy X, L605, and Rene 41 and the following refractory metals: (1) B66 and D43 columbium alloys, (2) T111 tantalum alloy, and (3) TZM molybdenum alloy. The brazing filler metals were NX-77 (Ni-7Si-5Fe-5Cr-4Co-3W-0.7B-0.1Mn), Hastelloy C, and Pd-40Ni. The results of the brazing studies are shown in Table 11.

The diffusion welding of dissimilar refractory metals was investigated by Young and Jones.[91] Columbium alloys Cb-1Zr and F-48 were joined to molybdenum alloy Mo-0.5Ti in a vacuum at temperatures of 1800 and 2000 F. The small disk specimens were assembled in a molybdenum capsule; pressure was applied by means of a screw threaded into the capsule. Excellent joining was achieved in both cases. No diffusion layer at the interface was noted, since these metals form mutual continuous solid solutions.

Vacuum-diffusion welding was investigated by D'Annessa as a method to join Mo-0.5Ti molybdenum alloy to unalloyed molybdenum and tungsten.[149] The research was directed toward the selection of intermediate metals that could be used to promote welding at temperatures below the recrystallization temperatures of the respective base metals. The intermediate metal foils investigated during this program include unalloyed nickel, titanium, columbium, and tantalum. The welds were made in a partial vacuum of 20 microns; after welding, the joints were subjected to diffusion treatments conducted at 2050 F for 30, 54, and 78 hours in a vacuum. Based on metallographic studies of welded diffusion couples between the base metals and the intermediate metals, it was concluded that optimum joining occurred with titanium and columbium foils.

Extensive research has been conducted to join the refractory metals to graphite for aerospace and nuclear applications. A variation of diffusion welding, eutectic diffusion brazing, was used by Bondarev to join molybdenum, columbium, and tantalum to graphite.[150] A titanium-foil insert, electroplated with 0.0008 to 0.001-inch-thick layer of copper, was placed between the graphite and the refractory metal. Joining was conducted under the following conditions: (1) temperature - 1634 to 1841 F, (2) pressure - 43 to 100 psi, and (3) time - 5 to 10 minutes. Under these conditions, the titanium-copper eutectic alloy formed and wet the graphite and the refractory metal.

Columbium alloy Cb-1Zr has been brazed to two types of graphite for a space radiator application using the following filler metals: (1)

TABLE 11. TEST DATA DERIVED FROM BRAZED LAP JOINTS OF DISSIMILAR METALS[145]

Dissimilar Materials Joined by Brazing: Superalloy Component	Dissimilar Materials Joined by Brazing: Refractory-Metal-Foil Component	Braze Alloy	Braze Cycle (Vacuum)	Brazing Characteristics (Wetting, Flow, Lap Penetration, and Filleting)	Lap Shear Tests of Brazed Specimens, Argon Atmosphere. Tensile Stress in Refractory Foil and Superalloy Components at Point of Specimen Failure (Maximum Stresses, ksi): Room Temperature, Superalloy	Room Temperature, Refractory Foil	2000 F, Superalloy	2000 F, Refractory Foil	Relative Toughness of Braze Bonds - Determined by Simple Peel Tests of Brazed Lap Joints (Room Temperature)
Hastelloy X (0.029 in.)	B66 (0.012 in.)	NX-77	2260 F, 5 min	Very good	--	83.3[a]	10.1[a]	24.4	Good
	D43 (0.006 in.)	NX-77	2260 F, 5 min	Very good	--	60.7[a]	9.2[a]	44.6	Good
	T111 (0.012 in.)	NX-77	2280 F, 5 min	Very good	--	98.0[a]	15.0[a]	37.4	Good
	TZM (0.012 in.)	NX-77	2280 F, 5 min	Very good	--	35.7[a]	11.9	29.0[a]	TZM component delaminates at low stress level. Braze bond intact.
L605 (0.030 in.)	B66 (0.012 in.)	NX-77	2260 F, 5 min	Very good	--	75.5[a]	12.0[a]	29.6	Good
	D43 (0.006 in.)	NX-77	2260 F, 5 min	Very good	--	77.4[a]	9.1[a]	22.6	Good
	T111 (0.012 in.)	NX-77	2280 F, 5 min	Poor wetting, flow and lap penetration	--	--	--	--	Very poor
	TZM (0.012 in.)	NX-77	2280 F, 5 min	Poor wetting, flow and lap penetration	--	--	--	--	Very poor
René 41 (0.043 in.)	B66 (0.012 in.)	NX-77	2225 to 2260 F, 5 min	Poor; excessive formation of liquid metal at braze temperatures, uncontrollable	--	--	--	--	Very poor
	D43 (0.006 in.)	NX-77	2225 to 2260 F, 5 min	Poor; excessive formation of liquid metal at braze temperatures, uncontrollable	--	--	--	--	Very poor
	T111 (0.012 in.)	NX-77	2280 F, 5 min	Poor wetting, flow and lap penetration	--	--	--	--	Very poor
	TZM (0.012 in.)	NX-77	2280 F, 5 min	Very good	--	73.0[a]	6.4[a]	22.8	TZM component delaminates at low stress level. Braze bond intact.
L605 (0.030 in.)	B66 (0.012 in.)	Hastelloy C	2360 to 2380 F, 5 min	Good; braze slightly erosive to B66 foil, vicinity of braze load	--	91.3[a]	15.8[a]	36.4	Good
	D43 (0.012 in.)	Hastelloy C	2360 to 2380 F, 5 min	Very good	--	76.0[a]	14.1[a]	32.6	Good
	T111 (0.012 in.)	Hastelloy C	2360 to 2380 F, 5 min	Good; braze slightly erosive to T111 foil, vicinity of braze load	--	99.8[a]	12.2[a]	10.0	Good
	TZM (0.012 in.)	Hastelloy C	2360 to 2380 F, 5 min	Good; braze slightly erosive to TZM foil, vicinity of braze load	--	37.4[a]	15.4[a] (Simultaneous failures)	38.5[a]	TZM component delaminates at low stress level. Braze bond intact
Hastelloy X (0.029 in.)	B66 (0.012 in.)	Hastelloy C	2360 to 2380 F, 5 min	Very good	--	101.0[a]	17.1[a]	42.4	Good
	D43 (0.012 in.)	Hastelloy C	2360 to 2380 F, 5 min	Fair to good (excess liquid formation, controllable)	--	85.2[a]	10.4[a]	25.2	Good
	T111 (0.012 in.)	Hastelloy C	2360 to 2380 F, 5 min	Very good	--	107.5[a]	13.6[a]	32.9	Good
	TZM (0.012 in.)	Hastelloy C	2360 to 2380 F, 5 min	Fair; good wetting, flow and lap penetration, but accompanied by heavy, unmelted residual (variable filleting)	--	--	--	--	TZM component delaminates at low stress level. Braze bond intact
René 41 (0.062 in.)	B66 (0.012 in.)	Hastelloy C	2360 to 2380 F, 5 min	Good; excess liquid formation, controllable	--	32.8[a]	>8.6 (Failure of mechanical linkage)	>44.3	Good
	D43 (0.012 in.)	Hastelloy C	2360 to 2380 F, 5 min	Good; excess liquid formation, controllable	--	47.5[a]	5.3	27.4[a]	Good
	T111 (0.012 in.)	Hastelloy C	2360 to 2380 F, 5 min	Very good	--	101.0[a]	3.5[a]	12.4	Good
	TZM (0.012 in.)	Hastelloy C	2360 to 2380 F, 5 min	Fair; good wetting, flow and lap penetration, but accompanied by heavy, unmelted residual (variable filleting)	--	--	--	--	TZM component delaminates at low stress level. Braze bond intact.
Hastelloy X (0.029 in.)	B66 (0.012 in.)	60Pd-40Ni	2375 F, 5 min	Very good	--	66.7[a]	16.2	39.2[a]	Good[b]
	D43 (0.012 in.)	60Pd-40Ni	2375 F, 5 min	Fair to good; marginal filleting behavior	--	73.7[a]	17.2[a]	41.7	Good[b]
	T111 (0.012 in.)	60Pd-40Ni	2375 F, 5 min	Very good	--	108.0[a]	16.2 (Braze joint failure)	39.1	Good[b]
	TZM (0.012 in.)	60Pd-40Ni	2375 F, 5 min	Very good	--	106.0[a]	16.4[a]	39.9	TZM component delaminates at low stress level. Braze joint intact.[b]
L605 (0.030 in.)	B66 (0.012 in.)	60Pd-40Ni	2375 F, 5 min	Fair; braze erosive to B66 foil	--	--	--	--	Very poor
	D43 (0.012 in.)	60Pd-40Ni	2375 F, 5 min	Fair; braze erosive to D43 foil	--	--	--	--	Very poor
	T111 (0.012 in.)	60Pd-40Ni	2375 F, 5 min	Very good	--	109.0[a]	17.0 (Braze joint failure)	44.6	Good[b]
	TZM (0.012 in.)	60Pd-40Ni	2375 F, 5 min	Very good	--	105.0[a]	17.5[a]	45.3	TZM component delaminates at low stress level. Braze joint intact.[b]
René 41 (0.062 in.)	B66, D43, T111, TZM (0.012 in.)	60Pd-40Ni	2375 F, 5 min	Very poor; excessive formation of liquid metal at braze temperature, uncontrollable	--	--	--	--	Very poor

(a) Indicates component that failed in lap shear test.
(b) Braze fillets prone to crack when joint is lightly flexed by hand.

Ag-26Cu-8Ti, (2) Ti-48Zr-4Be, and (3) Au-10Ni-5Fe; brazing was done in a vacuum of 10^{-5} torr.[151] The brazing alloys were deposited on the metal substrates by plasma-arc spraying procedures; the alloy compositions were adjusted to compensate for the losses of titanium and beryllium during spraying. The thermal stability and integrity of the joints were evaluated by aging (500 hours at 1350 F) and thermal cycling (500 cycles from 350 to 1350 F) tests conducted in a vacuum; all joints remained sound after these tests. Cb-1Zr-to-graphite joints were also encapsulated and aged at 1350 F for 2,500 hours and 4,000 hours without encountering problems with joint integrity.

Filler metals have been developed to join molybdenum to graphite in association with a program on molten-salt reactor.[152] These alloys had to wet graphite and molybdenum readily and be resistant to corrosion by molten fluoride salts. Numerous alloys in the nickel-gold-molybdenum and nickel-gold-tantalum alloy systems were prepared and evaluated by brazing tests conducted at 2370 F. In the Ni-Au-Ta system, an alloy with the composition Au-10Ni-30 Ta was most effective in brazing molybdenum-to-graphite and graphite-to-graphite joints; however, this alloy had limited ductility and fillet cracking was observed. More promising filler metals were found in the Ni-Au-Mo alloy system. The alloy, Au-35Ni-30Mo, wet graphite readily and flowed well; it proved to be suitable for brazing molybdenum-to-graphite joints.

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13. ABSTRACT

In this report, the dissimilar-metal joining between the following metals and alloys is emphasized: (1) aluminum, titanium, and beryllium, and their alloys, (2) refractory metals and alloys, and (3) high-strength steels and other high-strength, heat-resistant alloys. Dissimilar-metal joints in structures having aerospace applications are emphasized. Joining technology is discussed in the following major sections:

(1) Joining dissimilar ferrous metals
(2) Joining nonferrous to ferrous metals
(3) Joining dissimilar nonferrous metals.

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Copper base alloy						
Magnesium						
Nickel base alloys						
Stainless steels						
High alloy steels						
Columbium						
Molybdenum						
Tungsten						
Tantalum						
Diffusion welding						
Steels						
Refractory metals						